The Coma Dust of Comet C/2013 US10 (Catalina): A Window into Carbon in the Solar System

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Abstract

Comet C/2013 US10 (Catalina) was a dynamically new Oort cloud comet whose apparition presented a favorable geometry for observations near close-Earth approach (≈0.93 au) at heliocentric distances <2 au when insolation and sublimation of volatiles drive maximum activity. Here we present mid-infrared 6.0 μm silicate feature attributed to Mg-rich crystalline olivine and the submicron grain-size distribution peaking at ≈0.6 μm. The 10 μm silicate feature was weak, ≈12.8 ± 0.1% above the local continuum, and the bolometric grain albedo was low (≈14%). Comet C/2013 US10 (Catalina) is a carbon-rich object. This material, which is well represented by the optical constants of amorphous carbon, is similar to the material that darkens and reddens the surface of comet 67P/Churyumov–Gerasimenko. We argue this material is endemic to the nuclei of comets, synthesizing results from the study of Stardust samples, interplanetary dust particle investigations, and micrometeoritic analyses. The atomic carbon-to-silicate ratio of comet C/2013 US10 (Catalina) and other comets joins a growing body of evidence suggesting the existence of a C/Si gradient in the primitive solar system, providing new insight into planetesimal formation and the distribution of isotopic and compositional gradients extant today.

Unified Astronomy Thesaurus concepts: Long period comets (933); Coma dust (2159); Interplanetary dust (821); Astrophysical dust processes (99); Near infrared astronomy (1093)

1. Introduction

Traces of primordial materials, and their least-processed products, are found in the outermost regions of the solar system in the form of ices of volatile materials (H2O, CO, CO2, and other more rare species) and more refractory dust grains. This is the realm of comets. Nevertheless, it is certain that this outer region beyond the frost line was not entirely “primordial” but was “polluted” with the processed materials from the inner disk, the “hot nebular products,” (Harker & Desch 2002; Wooden et al. 2007; Ciesla 2011; Brownlee 2014), where gas–gas and gas–grain reactions occurred (Gail 2002, 2004; Gail & Trieloff 2017). There is considerable evidence that in the cold regions where cometary material formed, forming comet bodies were “salted” with refractory material processed at much higher temperatures (Zolensky et al. 2006).

Considerable effort has been expended to characterize the nature of refractory cometary materials to understand the environment of the early solar system from pebbles to planetesimals to larger bodies (see Poulet et al. 2016 and references therein). These grains likely are minimally processed over the age of the solar system after incorporation into the nuclei of comets. Information on the nature of these grains comes from a variety of sources, including remote sensing through telescopic observations (ground based, airborne, and space based), rendezvous/encounter experiments (e.g., Giotto, Rosetta/Philae, Deep Impact), collection of interplanetary dust particles (IDPs) in Earth’s stratosphere, and a sample return mission (Stardust). All of these activities have made important contributions to our understanding of these grains. The most detailed information we have come from the latter two types of studies, where laboratory analysis is possible. Yet, the IDPs from comets 81P/Wild 2 and 26P/Grigg-Skjellerup are vastly different. The former contains material processed at high temperature (Zolensky et al. 2006), while the latter is very “primitive” (Busemann et al. 2009). For these reasons, it is necessary to determine as best as we can the properties of dust grains from a large sample of comets using remote techniques (Cochran et al. 2015). These include observations of both the thermal (spectro-photometric) and scattered light (spectrophotometric and polarimetric). The former technique provides our most direct link to the composition (mineral content) of the grains.

With these data, combined with modeling features in the infrared spectral energy distributions (SEDs) arising from mineral species emitting in the comet coma (dust grains) and
Table 1
Observational Summary—Comet C/2013 US10 (Catalina)

| Mean Date | Observation | Instrument | Grism or Filter | Single Frame Exposure | Total On Source Integration | Tail a | Tail b |
|-----------|-------------|------------|-----------------|-----------------------|-----------------------------|-------|-------|
| 2016 UT (dd-mm hr:min:s) | Configuration | λc (μm) | Time (s) | Time (s) | rb (au) | Δ (au) | Ang (°) | Vector | anti-Sun Gas | Vector | anti-velocity Dust |
| NASA SOFIA | FORCAST (FOF276) | Imaging SWC | 7.70 | 23.88 | 477.52 | 1.710 | 1.106 | 32.96 | 103.54 | 23.31 |
| 02-10T07:06:59.6 | Imaging Dual | 11.01 | 18.79 | 244.28 | ... | ... | ... | ... | ... |
| 02-10T07:29:47.6 | Imaging SWC | 7.70 | 24.90 | 498.07 | 1.697 | 1.080 | 33.06 | 106.50 | 24.80 |
| MORIS | FORCAST (FOF275) | Imaging SWC | 7.70 | 24.90 | 498.07 | 1.697 | 1.080 | 33.06 | 106.50 | 24.80 |
| 02-09T08:09:23.3 | Imaging SWC | 7.70 | 24.90 | 498.07 | 1.697 | 1.080 | 33.06 | 106.50 | 24.80 |
| 02-09T08:31:48.8 | Imaging Dual | 11.01 | 18.79 | 244.28 | ... | ... | ... | ... | ... |
| 02-09T08:31:48.8 | Imaging SWC | 7.70 | 24.90 | 498.07 | 1.697 | 1.080 | 33.06 | 106.50 | 24.80 |
| NASA IRTF | Imaging Dual | 11.01 | 18.79 | 244.28 | ... | ... | ... | ... | ... |
| 02-09T08:31:48.8 | Imaging SWC | 7.70 | 24.90 | 498.07 | 1.697 | 1.080 | 33.06 | 106.50 | 24.80 |
| BASS | Imaging Optical | SDSS i′ | 5.00 | 20.00 | 1.315 | 0.747 | 47.80 | 292.10 | 157.27 |
| 01-11T15:11:06.6 | Imaging Optical | SDSS i′ | 5.00 | 20.00 | 1.315 | 0.747 | 47.80 | 292.10 | 157.27 |
| 01-10T14:34:30.0 | IR Spectra | 2.6–14.2 | 960.00 | 4800.00 | 1.307 | 0.758 | 48.72 | 293.42 | 157.37 |

Notes.

a Observation geometry calculated by JPL Horizons (Giorgini et al. 1996).
b Vector direction measured CCW (eastward) from celestial north on the plane of the sky.

Dynamical models of solar system formation and planetary migration, we can address fundamental questions of solar system formation. These question include: what was the method of transport of these materials, and has information on the scale of those transport processes been stored in primitive solar system objects? Do comets, the remnants of that epoch, still contain clues as to what happened?

In this paper, we report our post-perihelion (TP = 2015 November 15.721 UT) spectrophotometric observations of comet C/2013 US10 (Catalina), a dynamically new (see Oort 1950, for a definition based on orbital elements) Oort Cloud comet with 1/a<sub>orb</sub> = 5.3 × 10<sup>-6</sup> au<sup>-1</sup> (Williams 2019) and discuss important new interpretations that the coma grain composition of comets from remote-sensing observations can bring to understanding dust processing in the primitive solar system.

2. Observations

Infrared and optical observations of C/2013 US10 (Catalina) were conducted at two contemporaneous epochs near close-Earth approach (Δ ≈ 0.93 au) with the NASA IRTF Array Spectrograph System (BASS; Hackwell et al. 1990) during the early morning (daytime) hours. BASS has no moving parts and observes all wavelengths in its 2–14 μm operable range using two 58 element block impurity band linear arrays simultaneously through the same aperture. All observations were obtained with a fixed 4″0 diameter circular aperture. Standard infrared observing techniques were employed, using double-beam mode with a chop/nod throw of ≈60″. Sprague et al. (2002) provide a detailed description of the BASS data acquisition and preliminary reduction scheme. Nonsidereal tracking of the comet by the IRTF telescope was performed using Jet Propulsion Laboratory (JPL) Horizons’ (Giorgini et al. 1996) generated rates, and fine guiding, to keep the comet photocenter in the BASS aperture, was done either by manually guiding on the visible comet image produced by the BASS sky-filtered visible CCD camera, or off a strip chart using thermal channels of the BASS array.

Photometric calibration of individual comet data sets was performed using observations of α Boo observed at equivalent airmass to minimize telluric corrections. α Boo is a well-characterized infrared standard for ground- and space-based telescopes and has been extensively monitored and modeled by the BASS instrument team and other investigators for decades. The calibration and telluric corrections are uncertain to within ≈5%. Examination of independent, flux-calibrated spectra of comet C/2013 US10 (Catalina) obtained during the course of the 2016 January 10.61 UT observational campaign showed no variance in the flux level of the SED (i.e., no outbursts or jet-induced changes in coma brightness were witnessed) or spectral shape. Hence, all spectra were averaged together (with
the proper propagation of all statistical point-to-point uncertainties) to produce the final spectrum presented in Figure 1.

Optical imagery of the comet was obtained on 2016 January 11.633 UT with the NASA IRTF telescope (Gulbis et al. 2011) in a Sloan Digital Sky Survey (SDSS) i′ filter (λc = 0.7630 μm, filter FWHM of 0.1530 μm). Multiple exposures (5 s each) of the comet nucleus and surrounding coma were obtained using AB pairs nodding the telescope by 60″ and dithering the telescope while tracking at the nonsidereal rate corresponding to the predicted motion of the comet in an airmass range of ≈1.18. All images were corrected for overscan and bias with standard IRAF7 routines. The data were photometrically calibrated using GSC 02581–02323 (G2V) SDSS colors reported from SIMBAD transformed to the USNO system as described in Tucker et al. (2006), adopting 3631 Jy for zeroth magnitude. No color corrections for spectral type were applied in the transformation. The average nightly seeing was ∼2″2 as determined from the standard star. The observed i′ flux density of the comet measured in an equivalent BASS aperture was (2.316 ± 0.001) × 10^{-17} W cm^{-2} μm^{-1}. The resultant composite FORCAST spectra of comet C/2013 US10 (Catalina) is presented in Figure 2. Figure 3 presents panels for each individual grating segment, spanning the respective spectral grasp, to illustrate the spectral details of the observed SEDs.

Optical images in the SDSS i′ filter also were obtained on each flight series prior to the start of the mid-IR observing sequence using the Focal Plane Imager (FPI; Pfüller et al. 2016). The FPI + field of view is 8.7 arcmin², with a plate scale of 0″051 per pixel and a FWHM of ∼3″75. The comet was tracked using the JPL Horizons nonsidereal rates. These data frames were bias- and overscan-corrected using standard routines. The comet’s surface brightness was flux calibrated by using aperture photometry of seven stars in the image field of view with known i′ magnitudes taken from the USNO UCAC4 catalog to establish the photometric zero point (resultant fractional uncertainty of ≈1%).

February, conducted as part of our SOFIA comet programs (P.I. Woodward, AOR_ID 04_0010). Mid-infrared imaging observations of C/2013 US10 (Catalina) in three filters and the The Short Wavelength Camera (SWC) grism (G063) were obtained on the first flight, while on the second flight, imaging in the same three filters was repeated in addition to Long Wavelength Camera (LWC) grism observations with three gratings (G111, G227, and G329). For all spectroscopic observations, the instrument was configured using a long slit (4″7 × 191″), which yields a spectral resolution R = λ/Δλ ~ 140–300. The comet was imaged in the SWC using the F197 filter to position the target in the slit. Both imaging and spectroscopic data were obtained using a two-point chop/nod in the nod–match–chop (C2N) mode with 45″ chop and 90″ nod amplitudes at angles of 30°/210° in the equatorial reference frame.

The FORCAST scientific data products were retrieved from the SOFIA archive, after standard pipeline processing and flux calibration were performed (for details, see Clarke et al. 2015; Woodward et al. 2015). An extensive discussion of the FORCAST data pipeline can be found in the Guest Investigator Handbook for FORCAST Data Products, Rev. B8.

The computed atmospheric transmission at flight altitudes was used to clip out grism data points in wavelength regions where the transmission was less than 70%. Subsequently, to increase the signal-to-noise ratio (S/N) of the comet spectra, data in each grism spectra segment were binned using a weighted three-point boxcar. As there is no wavelength overlap between individual FORCAST grism segments, combined with an inherent uncertainty in the absolute grism flux calibration, and the fact that observations were conducted on separate nights, photometry derived from the image data was used to scale the grism data to a common SED. Integration of the observed grism data with the corresponding filter transmission profile lying within the respective grism spectral grasp (i.e., FORF111 for G111) was used to construct a synthetic photometric point. This latter photometric point was compared to the observed image aperture photometry derived within an equivalent circular diameter beam corresponding to the grism extraction aperture area (average for all grisms was 17″54 ± 0″074, derived data product keyword PSF_RAD). The grism scaling factor was derived from this ratio (≈8%). Neither the shape of the observed SED inferred from the image photometry nor the relative flux level of the SED changed significantly over the two epochs of the SOFIA observations.

The resultant composite FORCAST spectra of comet C/2013 US10 (Catalina) is presented in Figure 2. Figure 3 presents panels for each individual grating segment, spanning the respective spectral grasp, to illustrate the spectral details of the observed SEDs.

Mid-infrared (mid-IR) spectrophotometric observations of comet C/2013 US10 (Catalina) were obtained using the Faint Object InfraRed CAmera (FORCAST; Herter et al. 2018) mounted at the Nasmyth focus of the 2.5 m telescope of the SOFIA Observatory (Young et al. 2012). FORCAST is a dual-channel mid-IR imager and grism spectrometer operating from 5 to 40 μm.

The data were acquired on two separate, back-to-back flights, originating from Palmdale, CA, at altitudes of ≈11.89 km in 2016

Figure 1. Comet C/2013 US10 (Catalina)’s 3.0–14 μm BASS spectrum obtained on 2016 January 10.61 UT with the NASA IRTF telescope. This spectrum was derived by averaging all photometrically calibrated individual comet spectra obtained over a 1.33 hr interval. Regions of poor telluric transmission (≤30%) from atmospheric CO2 and H2O vapor have strong absorption bands result in gaps in the data where BASS spectral data points are clipped out. The red curve is the best-fit blackbody, TB = 265.3 ± 2.6 K fit to the local 10 μm continuum as described in Section 3.3. The excess over the blackbody curve at short wavelengths is due to scattered, reddened sunlight contributing substantially to the flux.

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7 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

8 https://www.sofia.usra.edu/Science/DataProducts/FORCAST_G1_Handbook_RevA1.pdf
FORCAST grism extraction aperture was equivalent circular aperture corresponding to the average SOFIA epoch of comet C\textsubscript{i} as described in Section 3.3.

The observed $i'$ flux density of the comet measured in an equivalent circular aperture corresponding to the average SOFIA FORCAST grism extraction aperture was $(8.215 \pm 0.009) \times 10^{-17}$ W cm$^{-2}$ μm$^{-1}$.

3. Discussion

3.1. SOFIA Imagery and Photometry

Images of comet C/2013 US\textsubscript{10} (Catalina) obtained during the 2016 February 9 UT flight are presented in Figure 4. Examination of the azimuthally averaged radial profiles of the comet in each filter reveals comet C/2103 US\textsubscript{10} (Catalina) exhibited extended emission beyond the point-spread function (PSF) of point sources observed with FORCAST under optimal telescope jitter performance in each filter.\footnote{http://www.sofia.usra.edu/Science/ObserversHandbook/FORCAST.html} Centroiding on the photocenter of the comet nucleus, photometry in an effective circular aperture of radius 13 pixels, corresponding to 9\arcsec984, with a background aperture annulus of inner radius 30 pixels (23\arcsec58) and outer radius of 60 pixels (47\arcsec16), was performed on the Level 3 pipeline coadded (.COA) image data products using the Aperture Photometry Tool (APT v2.4.7; Laher et al. 2012). The photometric aperture is $\approx 3 \times$ the nominal point-source FWHM and encompassed the majority of the emission of the comet and coma. Sky-annulus median subtraction (APT Model B as described in Laher et al. 2012) was used in the computation of the source intensity. The stochastic source intensity uncertainty was computed using a depth of coverage value equivalent to the number of coadded image frames. The calibration factors (and associated uncertainties) applied to the resultant aperture sums were included in the Level 3 data distribution and were derived from the weighted average calibration observations of α Boo.

The resultant SOFIA photometry is presented in Table 2. For the SOFIA epoch of comet C/2013 US\textsubscript{10} Catalina, the coma did not appear to have jets or active areas creating discernible coma structures by our visual examination of the photometric images divided by their azimuthally averaged radial profiles.

3.2. Dust Thermal Models of Infrared Spectra

Infrared spectroscopic observations are fitted with thermal models using standard spectral fitting techniques that minimize $\chi^2$. Interpreting thermal models enables investigation into fundamental quantities of comet dust populations including (1) bulk composition, (2) silicate structures of disordered ("amorphous silicates") and/or crystalline forms (forsterite and enstatite), (3) particle structures and size distributions, and (4) coma bolometric albedo. Refractory dust particles are much more robust in maintaining the chemical signatures from the time of formation (see Wooden et al. 2017) than the highly volatile ices and semirefractory organics with limited coma lifetimes (Dello Russo et al. 2016; Wooden et al. 2017). Semirefractory organics are known to exist through their limited lifetimes in comae and are presumed to be organics in the dust that are modified while in the coma. These are the so-called "distributed sources," distributed to the coma by the dust particles. The semirefractory organics are not (yet) observed in thermal IR spectroscopy but rather indirectly by the observed delayed release of molecules such as CO and/or H\textsubscript{2}CO as described in Disanti et al. (1999) and Cottin & Fray (2008) or by changes in the color of the scattered light (Tozzi et al. 2004). Polarization properties of particles are also dependent upon organics (Hadamik et al. 2020). Wooden et al. (2017) and Dello Russo et al. (2016) provide a detailed discussion of semirefractory organics in cometary comae.

Thermal emission spectroscopy when combined with thermal modeling probes the particle composition from the optically active material in comet coma. A number of approaches have been employed to model the dust thermal emission and study the composition of cometary particles. Usually, these involve the simultaneous use of a number of different grain compositions (mineralogy), a size distribution, and a description of the particle porosity. Radiative equilibrium is assumed when deriving particle temperatures, which are strongly composition-dependent as well as particle radii-dependent for low to moderate particle porosities. Particles of more highly absorbing compositions produce higher temperatures and higher flux density thermal emissions. To produce the combined emission of multiple compositions and integrated over grain-size distributions, thermal models may employ an ensemble (sums) of individual particles of homogeneous dust materials (Harker et al. 2002, 2011, 2017), or may employ composition “mixtures” calculated using effective medium theory (see Bockelée-Morvan et al. 2017a, 2017b).

At a given heliocentric ($r_{\odot}$/au) and geocentric ($\Delta$[au]) distance, the particle (dust) composition of optically active grains, comprising a linear combination of discrete mineral components, porous amorphous materials, and solid crystals in a comet’s coma can be constrained by nonnegative least-squares fitting of the thermal emission model spectra to the observed comet spectrum. The relative mass fractions and their respective correlated errors and the particle properties including the porosity and size distribution, having invoked a Hanner grain-size distribution (HGSD; Hanner 1983) for $n(\alpha)da$, are given as a prescription for the composition of coma particles (for details, see Harker et al. 2002, 2011, 2018, and references therein). The particle compositions of dust in the coma of comet C/2013 US\textsubscript{10} (Catalina) and relevant parameters from the best-fit thermal modeling are summarized in Table 3. The

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{C2013US10.png}
\caption{Comet C/2013 US\textsubscript{10} (Catalina)’s composite 4.9–36.5 μm FORCAST spectrum obtained with SOFIA on 2016 February 9.41 UT (mean UT of both nights). Regions of poor telluric transmission (≤70%) at flight altitudes result in gaps within certain wavelength intervals within each individual grism where FORCAST spectral data points are clipped out. The red curve is the best-fit blackbody that yields a $T_{BB} = 239.5 \pm 0.5$ K fit using all wavelengths ≥6.0 μm as described in Section 3.3.}
\end{figure}
uncertainties on the derived thermal model parameters reflect the 95% confidence limits that result from 1000 Monte Carlo trials (Harker et al. 2018). Figures 5 and 6 show the resultant models.

3.2.1. Optical Properties and IDP Analogs

A particle’s composition, structure (crystalline or amorphous), porosity, and effective radius (a) determine its absorption and emission efficiency, $Q_{abs}$ (a grain’s absorption efficiency and emission efficiency are equivalent at any given wavelength through Kirchhoff’s law). For an individual particle of effective radius $a$, $F_{\lambda}(a) \propto \pi \times a^2 \times Q_{abs}(a) \times B_{\lambda}(T_{dust}(a), \text{composition})$, where $B_{\lambda}$ is the Planck blackbody function, evaluated as a function of grain temperature, $T(K)$, particle size, and particle composition (Harker et al. 2002).

Our model uses optical constants ($n, k$) of five materials (see Harker et al. 2002; Hanner & Zolensky 2010; Wooden et al. 2017, and references therein) to compute $Q_{abs}(a)$: a Mg-rich crystalline olivine, forsterite with a mineralogy of $(\text{Mg}_{y},\text{Fe}_{1-y})_{2}\text{SiO}_{4}$, where $0.9 \leq y \leq 1.0$ (Jaeger et al. 1998); a Mg-rich crystalline orthopyroxene, enstatite $(\text{MgSiO}_3$; Jaeger et al. 1998); amorphous carbon (Edoh 1983);\(^{10}\) and amorphous silicates of pyroxene type and of olivine type with compositions similar to the stoichiometry of chondritic pyroxene $(\text{Mg}_{x},\text{Fe}_{1-x})\text{SiO}_3$ ($x = 0.5$ i.e., Mg:Fe = 50:50) and olivine $(\text{Mg}_{y},\text{Fe}_{1-y})_2\text{SiO}_4$ ($y = 0.5$ i.e., Mg:Fe = 50:50; Dorschner et al. 1995). The amorphous silicates produce the broad width of the the 10 μm silicate feature. When present, amorphous pyroxene generates a shorter wavelength shoulder on the 10 μm silicate feature. The crystalline materials are responsible for the sharp peaks in the IR spectra of comets at 11.15–11.2, 19.5, 23.5, 27.5, and 33 μm (see Crovisier et al. 1997; Harker et al. 2018). Absence of the latter crystalline spectral features in the observed IR SED does not imply that such species are absent in cometary comae (Harker et al. 2018). However, without detection of spectral features, these species cannot be well constrained by fitting thermal models to the mid-IR SEDs.

\(^{10}\) Amorphous carbon is used by many modelers (see Bockelée-Morvan et al. 2017a; Rinaldi et al. 2017).
The optical properties of the materials used in the radiative equilibrium calculations for particle temperatures are derived from either laboratory-generated materials or mineral samples from nature. Materials chosen for our thermal models have available optical constants and are found in or are analogous to materials in cometary samples. Crystalline silicates in IDPs (Wooden et al. 2000), Stardust, and ultracarbonaceous Antarctic micrometeorites (UCAMMs; Duprat et al. 2010) are of olivine and pyroxene compositions with a range of Mg:Fe contents with typically $1.0 \leq y \leq 0.5$ and $1.0 \leq x \leq 0.5$ (Brunetto et al. 2011; Dobriceanu et al. 2012; Frank et al. 2014; Joswiak et al. 2014; Wooden et al. 2017). Only Mg-rich crystalline olivine resonances have thus far been detected definitively in multiple comets using both the mid- and far-IR resonances. Laboratory studies of crystalline olivine by Koike et al. (2013) show that with decreasing Mg content (i.e., with $y < 0.8$), the 11.2 μm peak shifts toward 11.4 μm and the far-IR resonances dramatically change to different central wavelengths with different relative intensities. However, these more fayalitic crystalline olivine resonances have not been detected in comet comae.

Amorphous silicates and amorphous carbon in thermal models are considered candidate interstellar medium (ISM) or dense cloud materials (Wooden et al. 2017). The outer cold disk where comet nuclei accreted is a likely reservoir of inherited interstellar grains (Sterken et al. 2019). However, modeled characteristics of interstellar grains and measured cometary organics differ. Matrajt et al. (2005) persistently suggest that the origin of the organic fraction of cometary IDPs is a different environment than the diffuse ISM (DISM) because (a) the 3.4 μm band of organics in anhydrous IDPs is significantly narrower than in the DISM (e.g., toward the

Figure 4. Comet C/2013 US10 (Catalina) FORCAST filter imagery obtained with SOFIA on 2016 February 10.310 UT (mean UT). The image panels are (a) F077 = 7.70 μm, FWHM = 5".39; (b) F111 = 11.01 μm, FWHM = 4".23; (c) F197 = 19.70 μm, FWHM = 4".47; and (d) F315 = 31.36 μm, FWHM = 4".76. The vector indicating the direction of the comet’s motion and the vector indicating the direction toward the Sun are also provided. Images were centroided and shifted using the Fourier transform technique to the measured photocenter of the F197 image and smoothed with a three-pixel width median boxcar filter.

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Table 2
SOFIA Aperture Photometry and $c_f$ of Comet C/2013 US10 (Catalina)

| Date          | Filter | InstCfg | $\lambda_c$ ($\mu$m) | $\lambda F_{\lambda}$ ($\times 10^{-16}$ W cm$^{-2}$) | $c_f$ (cm) |
|---------------|--------|---------|----------------------|------------------------------------------------------|------------|
| 02-10T07:06:59.6 | SWC    | 02-10T07:06:59.6 | 7.0                  | 3.238 ± 0.141                                        | 1.261 ± 0.055 | 7096 ± 308 |
| 02-10T07:06:59.6 | Dual   | 02-10T07:06:59.6 | 11.01                | 13.823 3 ± 0.415                                     | 3.767 ± 0.113 | 7881 ± 236 |
| 02-10T07:06:59.6 | Dual   | 02-10T07:06:59.6 | 19.70                | 32.467 0.423                                        | 4.941 ± 0.064 | 8522 ± 111 |
| 02-10T07:06:59.6 | Dual   | 02-10T07:06:59.6 | 31.36                | 29.304 0.303                                        | 2.801 ± 0.029 | 8677 ± 90  |

Notes.

a Measured in a circular aperture with a radius of 17.664 centred on the photocenter of the comet nucleus.

b Aircraft climbing from 12.497 to 13.106 km during observations.

Table 3
Derived Grain Composition of Comet C/2013 US10 (Catalina)

| Thermal Model SED Details | SOFIA Spectra$^a$ | BASS Spectra$^b$ | Relative Mass Sub-µm Grains | Relative Mass Sub-µm Grains |
|---------------------------|-------------------|-----------------|-----------------------------|-----------------------------|
| (N$_p$ × 10$^{20}$)$^d$   |                   | (N$_p$ × 10$^{20}$)$^d$ |                     |              |
| Dust Components           |                   | Relative Mass Sub-µm Grains |                     |              |
| Amorphous pyroxene (AP)   | 0.132$^{+0.014}_{-0.014}$ | 0.242$^{+0.022}_{-0.023}$ | 0.630$^{+0.046}_{-0.049}$ | 0.174$^{+0.119}_{-0.134}$ |
| Amorphous olivine (AO)    | 0.029$^{+0.007}_{-0.013}$ | 0.053$^{+0.014}_{-0.013}$ | 0.515$^{+0.042}_{-0.042}$ | 0.147$^{+0.115}_{-0.108}$ |
| Amorphous carbon (AC)     | 0.567$^{+0.003}_{-0.003}$ | 0.473$^{+0.017}_{-0.015}$ | 4.582$^{+0.116}_{-0.115}$ | 0.574$^{+0.083}_{-0.075}$ |
| Crystalline olivine (CO)  | 0.072$^{+0.009}_{-0.009}$ | 0.232$^{+0.022}_{-0.024}$ | 0.233$^{+0.023}_{-0.023}$ | 0.11$^{+0.123}_{-0.111}$ |
| Crystalline pyroxene (CP) | 0.000              | 0.000            | 0.000                        | 0.000                        |

Resultants

| Total mass of submicron grains (gm) × 10$^{5}$ | 0.942$^{+0.039}_{-0.031}$ | ... | 4.853$^{+0.725}_{-0.699}$ | ... |
| Amorphous silicate dust fraction | 0.295$^{+0.015}_{-0.014}$ | ... | 0.315$^{+0.066}_{-0.067}$ | ... |
| Crystalline silicate dust fraction | 0.232$^{+0.022}_{-0.024}$ | ... | 0.111$^{+0.121}_{-0.111}$ | ... |
| Silicate-to-carbon ratio$^c$ | 1.16$^{+0.024}_{-0.022}$ | ... | 0.743$^{+0.294}_{-0.220}$ | ... |
| Crystalline silicate mass to total silicate mass$^d$ | 0.441$^{+0.032}_{-0.035}$ | ... | 0.260$^{+0.217}_{-0.260}$ | ... |
| $a_v$($\mu$m)$^e$ | 0.7 | ... | 0.5 | ... |
| Fractal porosity ($D$) | 2.727 | ... | 2.727 | ... |

Other Parameters

| Hanner grain-size distribution M:N | 22.2:3.7 | ... | 13.6:3.4 | ... |
| Reduced $\chi^2$ | 4.98 | ... | 0.86 | ... |
| Degrees of freedom | 49 | ... | 168 | ... |

Notes.

$^a$ Uncertainties represent the 95% confidence level.

$^b$ Comet on 2016 January 10 UT $r_h = 1.30$ au, $\Delta = 0.76$ au.

$^c$ Comet 2016 February 9 UT $r_h = 1.09$ au.

$^d$ Number of grains, N$_p$, at the peak ($a_v$) of the Hanner grain-size distribution (HGS).

$^e$ Ratio represents the bulk mass properties of the materials in the models.

$^f$ $F_{\text{opt}}$ = $m_{\text{ca}}$/$[m_{\text{amorphous}} + m_{\text{ca}}]$ where $m_{\text{ca}}$ is the mass fraction of submicron crystals.

$^g$ Peak grain size (radius) of the Hanner GSD.

Galactic Center, which is a mixture of diffuse and dense cloud material and (b) the aliphatic chains in IDPs are longer (less ramified) than in the DISM, based on the $-\text{CH}_2/-\text{CH}_3$ ratio in IDPs.
make their way into protoplanetary disks such as our own. In translucent clouds, THEMIS carbon chemistry facilitates the growth of H-rich and aliphatic-rich matter, denoted a-C(H), which accretes and then coagulates to tens of nanometer-size particles through a complex set of chemical reactions. The carbon-chemistry backbones are carbon belt-like molecules with aromatic bonds (n-cyclacenes) and an important process is the epoxylation of the surface materials. The carbonaceous particles, upon return to the harsh UV interstellar radiation field evolve “toward an end-of-the-road H-poor and aromatic-rich a-C material” (Jones & Ysard 2019). Carbonaceous matter in cometary samples appear significantly less dominated by aromatic moieties than implied by THEMIS models. Stardust samples only reveal a small concentration of small polycyclic aromatic hydrocarbons (PAHs; Clemett et al. 2010). Carbon X-ray Absorption Near Edge Spectroscopy (C-XANES) spectra of Stardust and IDP organics show saturated aliphatic carbon bonds are more recurrent than aromatic C=C bonds as well as amorphous carbon being the only carbon form common between these samples and the Bells, Tagish Lake, Orgueil, and Murchison meteorites (Wirick et al. 2009; De Gregorio et al. 2017). Laboratory absorption spectra do not quantify amorphous carbon as it has no resonances, although its presence can be discerned through C-XANES (Keller et al. 2004; Messenger et al. 2008).

Amorphous carbon is found in many IDPs (Keller et al. 2004; Busemann et al. 2009; Wirick et al. 2009; Brunetto et al. 2011), but amorphous carbon is not discussed for all IDPs (Flynn et al. 2013; Ishii et al. 2018) nor for all extraterrestrial particulate samples from primitive small bodies, specifically UCAMMs (Dartois et al. 2018; Mathurin et al. 2019). Despite a diversity of bonding structures in cometary organics (Bardyn et al. 2017) as well as organic matter in asteroids, there is a severe paucity of optical constants (de Bergh et al. 2008). Typically, optical constants of relatively transparent tholins are combined with optical constants of highly absorbing amorphous carbon to darken the models for surfaces of outer ice-rich bodies (de Bergh et al. 2008). Hence, amorphous carbon, which is devoid of aromatic bond IR resonances, is the best choice for the highly absorbing carbonaceous matter in models of dark surfaces of ice-rich bodies as well as for cometary coma particles.

Amorphous silicates in thermal models are analogous to Glass with Embedded Metal and Sulfides (GEMS) in IDPs (see Floss et al. 2006; Brunetto et al. 2011; Bradley 2013; Ishii et al. 2018; Stroud et al. 2019). The ISM silicate absorption feature has spectral similarities to GEMS (Bradley 2013; Stroud et al. 2019), and radiation damage can explain the nonstoichiometry of GEMS (Jäger et al. 2016). An alternative high-temperature formation scenario for GEMS is proposed for the protoplanetary disk (Keller & Messenger 2011) but is challenged by the discovery of GEMS with interior organic matter that could not have survived temperatures above 450 K (Ishii et al. 2018). Amorphous silicates are ubiquitous component of IR spectra of cometary comae, and their radiation equilibrium temperatures require compositions of Mg:Fe $\approx$ 50:50 (Harker et al. 2002).

3.2.2. The Hanner Grain-size Distribution

Our modeling invokes the HGSD $n(a) = (1 - a_0/a)^M (a_0/a)^N$, where $a$ is the particle radius, where $a_0 = 0.1 \mu m$ is the minimum grain radius, and $M$ and $N$ are independent parameters (Hanner 1983; Hanner et al. 1994). The HGSD is a modified power law that rolls over at particle radii smaller than...
the peak radius $a_p = (M + N)/N$, which is constrained by the thermal model analyses.

3.2.3. Moderately Porous Particles

The optical properties of porous particles composed of amorphous materials may be calculated by incorporating "vacuum" as one of the material components (Bohren & Huffman 1983). Porous grains are modeled with an increasing vacuous content as expected for hierarchical aggregation, using the porosity prescription or fractional filled volume given by $f = 1 - (a/0.1\mu m)^{D-3}$, where $a$ is the effective particle radius, with the fractal dimension parameter $D$ ranging from $D = 3$ (solid) to $D = 2.5$ (fractal porous but still spherical enough to be within the applicability of Mie theory computations; Harker et al. 2002, 2011, 2018 and references therein). Particle porosity affects the observed spectra of comets because the porous grains are cooler than solid grains of equivalent radius as their vacuous inclusions make them less absorbent at UV-visible wavelengths (Harker et al. 2002). The porosity prescription parameter $D$ is coupled with the grain-size distribution slope parameter $N$, and the two parameters are simultaneously constrained when fitting IR SEDs. Increasing porosity (lowering $D$) decreases particle temperatures, which can be compensated for by increasing the relative numbers of smaller to larger grains by steepening the slope (increasing $N$) of the HGSD as illustrated in Figure 2 of Wooden (2002).

An extremely porous particle that is an aggregate of submicron compact monomers can have the same temperature as its monomers ($P(\alpha)_{\max} > 80\%;$ Xing & Hamner 1997) or ($P(\alpha)_{\max} > 99\%$ with $a \geq 5 \mu m$; Kolokolova et al. 2007). However, IR spectra of comets are not well fit by such extremely porous particles that are uniformly as hot as their submicron-radii monomers, regardless of particle size. Thermal models for observed IR spectra of comets need particle size distributions of moderately porous or solid particles. For a comet near 1.5 au, an HGSD has submicron- to micron-radii particles ($a_{\text{peak}} \lesssim 1 \mu m$) that produce warmer thermal emission under the 10–100$\mu m$ silicate feature and at shorter near-IR wavelengths, as well as larger cooler particles producing the decline in the thermal emission at longer (far-IR) wavelengths. Compared to a size distribution of compact solid particles ($D = 3$), a size distribution of moderately porous particles ($P(\alpha) \sim 66\%–86\%; D = 2.727$ to $D = 2.5$, $a_{\text{eff}} = 5 \mu m$) are cooler and produce enhanced emission at longer wavelengths while still producing a silicate emission feature with the observed contrast compared to the local “pseudo-continuum” (see Section 3.4). Hence, thermal models constrain the porosity of the amorphous materials (amorphous silicates and amorphous carbon), and the slope and the peak radius ($a_{\text{peak}}$) of the grain-size distribution (see Harker et al. 2002, 2011, 2018).

3.2.4. CDE Models of Solid Trirefrangent Silicate Crystals

Silicate crystalline particles are not well modeled as spheres by Mie theory because of their anisotropic optical constants and irregular shapes (Koike et al. 2010). Crystals are not modeled as porous particles or as mixed-material particles using effective medium theory because modeled resonant features do not match laboratory spectra of the same materials. Discrete solid crystals are better computed using the continuous distribution of ellipsoids (CDE) approach (Fabian et al. 2001) or the discrete dipole approximation (DDA; Lindsay et al. 2013). Crystals of sizes larger than $\sim 1 \mu m$ do not replicate the observed SEDs of comets (Min et al. 2005). CDE with $c$-axis elongated shapes reasonably reproduces laboratory spectra of crystalline forsterite powders (Fabian et al. 2001) and serves as a starting point for our thermal models. Discrete solid crystals with sizes from 0.1 to $1 \mu m$ are included in our admixture of coma dust materials. From our thermal models, we quote the relative mass fractions for the $\leq 1 \mu m$ portion of the HGSD in Table 3.

3.2.5. Comet Crystalline Silicates and Disk Transport

The presence of crystalline silicate materials in cometary spectra and in cometary samples indicates transfer of materials that formed in the inner protoplanetary disk to the outer disk (Brownlee et al. 2006; Zolensky et al. 2006; Westphal et al. 2017) where volatile ices (H$_2$O, CO, CO$_2$) were extant along with dust particles to become incorporated into cometary nuclei (Rubin et al. 2020). Crystalline silicates are relatively rare along lines of sight through the ISM (5–50%, Kemper et al. 2004) and toward embedded young stellar objects or compact H II regions (1%–2%, with a few sources at >3%; Do-Duy et al. 2020). A significant crystalline silicate component in cometary dust has been clearly demonstrated by laboratory examinations of Stardust (Frank et al. 2014) and IDPs (Zolensky & Barrett 1992; Busemann et al. 2009; Brownlee & Joswiak 2017). Crystalline silicate mass fractions (defined as $f_{\text{cryst}} = m_{\text{cryst}}/[m_{\text{amorphous}} + m_{\text{cryst}}]$, where $m_{\text{cryst}}$ is the mass fraction of crystals) derived from thermal models of cometary IR SEDs typically are $\sim 20%–55\%$ (Harker et al. 2002, 2007, 2011, 2018; Wooden et al. 2004; Woodward et al. 2011, and Appendix I). Detailed laboratory studies of cometary forsterite and enstatite crystals show a small fraction have mineralogical signatures of gas-phase condensation such as liquid-iron-manganese-enriched (LIME) compositions (Frank et al. 2014; Joswiak et al. 2017), $^{16}$O enrichments commensurate with early disk processes (Defouilloy et al. 2016, 2017, 2018), as well as condensation morphologies such as enstatite ribbons in anhydrous IDPs (Bradley et al. 1999).

Moreover, Stardust samples and some cluster IDPs contain olivine crystals with a wider range of Fe contents (10% $< Fe < 60\%$) than the low Fe contents of $\sim 10%–20\%$ deduced from the wavelengths of the resonances of olivine crystals in cometary spectra (Crovisier et al. 1996, 1997; Wooden et al. 2017). It is a puzzle as to why the spectral signatures of Fe-bearing crystalline silicates are not spectrally detected in comets (Wooden et al. 2017). The Fe-bearing olivine crystals are analogous by their minor element compositions to olivine $(Mg \lesssim 80\%)$ crystals in type II chondrules and are called microchondrules or chondrule fragments (Frank et al. 2014; Brownlee & Joswiak 2017). In Stardust samples, one 15 $\mu m$ size type II chondrule called “Iris” has an age-date of $\geq 3$ million years (with respect to calcium–aluminum-rich inclusion (CAI) formation) and is well modeled as an isolated igneous system (Gainsforth et al. 2015).

Stardust samples pose a number of challenging questions for disk models about the formation of the nucleus of comet 81P/Wild 2. How did particles radially migrate as late as a few million years in disk evolution to the regime of volatile ices of H$_2$O, CO, and CO$_2$? How did cometary dust minerals that condensed early in the disk evolution persist in the disk long enough to be incorporated into this particular cometary nucleus, that is, persist and not be lost via the inward movement of particles? As yet, satisfactory answers to either of these questions do not exist.
Silicate crystals, specifically referring to forsterite and enstatite that are the abundant Mg-rich silicate crystalline species in comets and/or cometary samples (Wooden et al. 2017), condensed at temperatures near 1800 K or possibly were annealed materials at temperatures near 1100–1200 K in shocks (Harker & Desch 2002) under low oxygen fugacity conditions (Wooden et al. 2007). Radial transport may have occurred through a combination of protoplanetary disk processes including advection, diffusion, turbulence and aerodynamic sorting, meridional flows, disk winds, and/or planetary migration (Gail 2004; Wehrstedt & Gail 2008; Hughes & Armitage 2010; Ciesla 2011; Vokrouhlický et al. 2019). Disk models with meridional flows (see Gail 2004) have been successful in predicting ~20% silicate crystalline mass fractions at disk radii of more than tens of astronomical units in <1 million years.

Radial transport by advection can work through disk wind angular momentum transport (Bai 2016) but can also be produced by turbulent viscosity in the bulk of the disk. Radial transport by diffusion requires turbulence. It is generally thought that magnetohydrodynamical (MHD) turbulence occurs only in the rarefied upper layers of the disk atmosphere, if at all (Bai 2016). However even without an MHD effect, there are two recently discussed hydrodynamical mechanisms for producing turbulence: convective overstability (CO) and vertical shear instability (VSI) that are either individually or collectively operative in various locations in the disk (for example, Pfeil & Klahr 2019). Meridional 2D flows are another robust feature of disk models when turbulence mechanisms are considered operative (Stoll et al. 2017; Lyra & Umurhan 2019). Yet, even the qualitative nature of this flow is debated. Meridional flows for 2D and alpha-disk models were outwards along the midplane and inwards above one scale height (see Gail 2004). Recent 3D models of meridional flow show that the outward flow is above one scale height so particles that are lofted by turbulence to above one scale height above the midplane can move outwards (Stoll et al. 2017; Pfeil & Klahr 2020). To date, meridional flows only are inferred from ALMA in 12CO observations of the >300 au outer disk regions of the ~5 million year old, more massive Herbig Ae/Be system HD 163296 (Powell et al. 2019; Teague et al. 2019). Large-scale gas motions are not yet observed for analogs of our protoplanetary disk but cometary crystalline mass fractions suggest inner disk materials moved over large distances.

Models without meridional flows also show the outward movement of small particles, merely following the outward advective motion of the gas, at certain radii and times. Estrada et al. (2016) show disk models (see their Figure 15) with a range of dust particle masses in which the maximum disk radius reached by particles of a specific particle mass (i.e., size) increases with time, i.e., some particles do move outward and the smaller particles are more successful in moving outwards. Porous particles have larger aerodynamic cross sections compared to solid particles of the same mass, so porous particles are favored in outward movement compared to solid particles (Estrada & Cuzzi 2016). Ciesla & Sandford (2012) simulate the migration of particles by randomized turbulent kicks and thereby nicely illustrate the large-distance motions of some particles.

As a complement to transport within the disk, centrifugally driven disk winds may deposit particles with sizes \( \geq 1 \mu m \) to the outer disk at early times, which “may be relevant to the origin of the 20 \( \mu m \) CAI-like particle discovered in one of the samples returned from comet 81P/Wild 2” (Giacalone et al. 2019), Abrahám et al. (2019) observed the brightest outburst to date from EX Lupi using VLTI MIDI interferometry and VLT VISIR IR spectroscopy. Within five years, practically all crystalline forsterite that had become enhanced in the inner disk disappeared from the surface of the inner disk. Over that time, the spectral resonances from olivine crystals shifted emphasis from the mid- to far-IR wavelengths, indicating that the crystals experienced outward movement.

Disk models are challenged to effectively transport as well as maintain solids in the outer protoplanetary disk against the inward drift of particles, especially as particles grow to “pebble” size and decouple from the gas. If models that treat particle coagulation, as well as particle collisional destruction, can maintain a population of fine-grained particles (i.e., smaller particles with lower Stokes numbers \( S_{\theta} \)), then outward movement of small particles with time occurs (see Estrada et al. 2016). Many studies have investigated how material that is injected into the disk spreads outwards and inwards with time (for example, Sengupta 2019). When turbulence is a driving mechanism for radial transport, then aerodynamics affects particle movements, and one can expect signatures of size sorting by \( S_{\theta} \propto \rho a \), where \( a \) is the particle radius and \( \rho \) is the average particle density (Cuzzi et al. 2001; Jacquet 2014). Stardust samples demonstrate that aerodynamic sorting in aggregate formation occurred for particles of olivine compared to FeS, which are denser than olivine (Wozniakiewicz et al. 2012, 2013). The Rosetta mission’s imaging studies showed that comet 67P/Churyumov–Gerasimenko’s particles are hierarchical aggregates of hundreds of microns to millimeter size with components that are submicron to tens of micron in size (Hornig et al. 2016; Gütter et al. 2019; Langevin et al. 2020). Stardust samples and Rosetta particle studies are commensurate with the idea that aggregate particle components of submicron to tens of microns in size may be favored over larger solid particles in their outward movement to the disk regimes of comet nuclei formation.

3.2.6. Revised Specific Density for Amorphous Carbon

Our thermal model adopts an amorphous carbon (Acar) specific density of \( \rho_A(\text{Acar}) = 1.5 \text{ g cm}^{-3} \) from a quoted value of \( \rho_A(\text{Acar}) = 1.47 \text{ g cm}^{-3} \) (Williams & Arakawa 1972) measured for the same amorphous carbon material from which our optical constants were derived (Edoh 1983; Hanner et al. 1994). This specific density of \( \rho_A(\text{Acar}) \) used in these analyses of comet C/2013 US10 (Catalina) herein represents a significant change from our prior thermal models and publications that used an assumed bulk density of carbon of 2.5 \text{ g cm}^{-3} (Lisse et al. 1998; Harker et al. 2002), which actually was a specific density slightly higher than that of graphite (2.2 \text{ g cm}^{-3} (Robertson 2002). The relative mass fractions of carbonaceous matter and siliceous matter are important and allow us to take a detailed look at the carbonaceous contribution of comets to the hypothesized gradient of carbon in the solar system (Section 3.9) and as discussed by other authors (Hendrix et al. 2016; Gail & Triloff 2017; Dartois et al. 2018). Tables 6–9 in the Appendix summarize the derived thermal model parameters from the observed IR SED for an additional set of comets using \( \rho_A(\text{Acar}) = 1.5 \text{ g cm}^{-3} \).

\[
11 \text{ Edoh optical constants are of glassy carbon or of an amorphous carbon from the Plessey Company (UK) Ltd., Caswell, Towcester, Northants, England (Williams & Arakawa 1972).}
\]

\[
12 \text{ If } \rho_A(\text{Acar}) = 2.5 \text{ cm}^{-3}, \text{ then comet C/2013 US10 (Catalina) would have yielded } C/S \approx 11, \text{ which is greater than } C/S \text{ for any 67P/Churyumov–}
\]

Gerasimenko particle measured by COSIMA on Rosetta (Bardyn et al. 2017).
For completeness, in our thermal models, the specific density of amorphous silicates is \( \rho \) (Asil) = 3.3 g cm\(^{-3} \) as discussed by Harker et al. (2002 and references therein).

### 3.3. Coma Dust Composition from Thermal Models

Comet C/2013 US\(_{10} \) (Catalina) is a dynamically new (DN) Oort cloud with eccentricity of \( \sim 1.0003 \). Compositionally, the dust in the coma of comet C/2013 US\(_{10} \) (Catalina) is carbon rich, and this comet is among a subset of observed comets that are similarly carbon rich, some of which are also DN. The carbon-rich dust particles of comet 67P/Churyumov–Gerasimenko were measured in situ to have by weight 55% mineral and 45% (carbonaceous) organic (see Figure 10, Bardin et al. 2017). If we consider their mineral-to-organic ratio to be analogous to our silicate-to-carbon ratio, then 67P/Churyumov–Gerasimenko has a ratio of 1.1 and C/2013 US\(_{10} \) (Catalina) has ratios of 1.55 and 1.03 for 1.3 au (BASS) and 1.7 au (FORCAST), respectively. However, within the thermal model parameter uncertainties, the silicate-to-carbon ratios are the same for both epochs. A decrease by a factor of 1.5 in the silicate-to-carbon ratio for the best-fit values between the two epochs is partly attributed to the definitive detection of crystalline forsterite at 1.3 au that increases the silicate mass fraction relative to the upper limit for forsterite at 1.7 au. Between the two epochs, the amorphous carbon increases by a factor of 1.21 (see Table 3).

The dust particle population in comet C/2013 US\(_{10} \) (Catalina) is characterized by a moderate particle porosity \( (D = 2.727) \). Coma grains extend to submicron-size particles; the HGSD (defined in Section 3.2.2) peaks at an average \( \mu = \{0.7, 0.5\} \) \( \mu \) m, with a grain-size distribution slope of \( N = \{3.4, 3.7\} \), respectively, for the two epochs at 1.3 au and 1.7 au. The derived coma dust properties of C/2013 US\(_{10} \) (Catalina) share similar characteristics to those found recently for some other long-period Oort cloud comets, such as C/2007 N3 (Lulin), which is also DN (Woodward et al. 2011).

The HGSD slope of comet C/2013 US\(_{10} \) (Catalina) is in the range of other comets, including Oort cloud comets, where typically \( 3.4 \leq N \leq 4 \). However, its HGSD slope is greater (steeper) than found for comet 67P/Churyumov–Gerasimenko, which has multiple measurements of its differential grain-size distribution \( n(a)/da \) with slopes of \( N = 3.0 \) (Bockelée-Morvan et al. 2017a, 2017b), \( N = 3.1 \) (Rinaldi et al. 2017), \( N = 3 \) (Della Corte et al. 2019), or \( N \approx 2.7–3.2 \) for \( a < 100 \) \( \mu \) m and \( N \approx 1.8 \) for \( 100 < a < 1000 \) \( \mu \) m (Merouane et al. 2016).

Examination of the SEDs of comet C/2013 US\(_{10} \) (Catalina) obtained at two different epochs and the thermal-model-derived parameters (Table 3) enable us to deconstruct and decipher aspects of the inner coma dust environment (Figures 5 and 6). From the 58% drop in the available ambient solar radiation between the 1.3 au (BASS epoch) and 1.7 au (SOFIA epoch) observations, one would expect on average the particles in the coma to be cooler at the latter epoch. From the long-wavelength shoulder (\( \lambda > 12.5 \) \( \mu \) m) of the 10 \( \mu \) m silicate feature and longward, the SED measured at 1.7 au (Figure 2) shows enhanced emission at longer wavelengths. Thus, the particles contributing to the far-IR emission are cooler at 1.7 au compared to those at 1.3 au as anticipated. However, the thermal emission at 7.8 \( \mu \) m and bluewards is similar for the two epochs. Hence, at 1.7 au, the coma of comet C/2013 US\(_{10} \) (Catalina) must have an increased abundance of smaller warm amorphous carbon particles. Moreover, the number of dust particles in the coma at 1.7 au is increased over that at 1.3 au in order to produce about the same flux density of thermal emission at these two epochs with the cooler particles present at 1.7 au.

There is evidence of a narrow 11.2 \( \mu \) m silicate feature attributable to Mg-rich crystalline olivine (Haner et al. 1994; Wooden 2008). This is borne out by the detailed thermal modeling of the SED, which Constrains the relative mass fraction of crystalline forsterite grains in the coma at 1.3 au. The ratio of the crystalline silicate mass to the total silicate mass was \( \sim 0.44 \). The crystalline mass fraction determined for comet C/2013 US\(_{10} \) (Catalina) is greater than that determined for other dynamically new comets such as C/2012 K1 (Pan-STARRS) studied with SOFIA (Woodward et al. 2015). The derived values for each observational epoch are summarized in Table 3.

For the portion of the grain-size distribution with radii \( a \leq 1 \) \( \mu \) m (the submicron population), the silicate-to-carbon ratio is 1.116+0.072−0.074 and 0.743+0.264−0.220 at 1.3 au and 1.7 au, respectively (see Table 3). Compared to 1.7 au, the higher silicate-to-carbon ratio at 1.3 au is partly due to a factor of \( \sim 1.25 \) less amorphous carbon combined with an increase in mass of silicates from the definitive detection of forsterite. This crystalline silicate material produces a sharp peak at 11.1–11.2 \( \mu \) m (Koike et al. 2010 and references therein) and is relatively transparent outside of its resonances. At 1.3 au, crystalline silicate mass fraction \( (f_{\text{sil}}) \) is 0.441+0.033−0.035 in the coma of comet C/2013 US\(_{10} \) (Catalina) so forsterite crystals contribute significantly to the silicate-to-carbon ratio. Crystalline silicates are tracers of radial migration of inner disk condensates or possibly shocked Mg-rich amorphous olivine so the 44% crystalline mass fraction indicates significant radial transport of inner disk materials out to the comet-forming regime (see Section 3.2.5).

### 3.4. Silicate Feature Shape and Strength

The spectral shape of the 10 \( \mu \) m silicate feature can be revealed by dividing the observed flux by a local 10 \( \mu \) m blackbody-fitted “pseudo-continuum.” The shape of the 10 \( \mu \) m silicate feature arises from emission from submicron- to at most several-micron-radii silicate particles in the comae, depending on the porosity. In thermal models, the “pseudo-continuum” has contributions from porous or solid amorphous carbon, which is featureless at all wavelengths. Thermal models require porous particles \( (D = 2.7272) \) for comet C/2013 US\(_{10} \) (Catalina). Figure 7 shows the silicate feature shape for comet C/2013 US\(_{10} \) (Catalina) from the BASS observations. The FORCAST mid-IR spectral data show a similar contrast silicate feature but with a lower S/N than the BASS data, so these data are not included in the figure for clarity.

The silicate strength parameter historically enables one to intercompare the dust properties of different comets by quantifying the silicate feature contrast with respect to the local “pseudo-continuum” (Sitko et al. 2004; Woodward et al. 2015). The 10 \( \mu \) m silicate feature strength, defined as \( F_{10}/F_{c} \), where \( F_{10} \) is the integrated silicate feature flux over a bandwidth of 10–11 \( \mu \) m and \( F_{c} \) is that of the local blackbody “pseudo-continuum” at 10.5 \( \mu \) m (Sitko et al. 2004), is a metric that describes the contrast of the silicate emission feature. We find the 10 \( \mu \) m silicate feature to be weak in comet C/2013 US\(_{10} \) (Catalina), approximately 12.8% ± 0.1% above the local “pseudo-continuum.” The low silicate feature strength in comet C/2013 US\(_{10} \) (Catalina) is similar to some other comets (Sitko et al. 2004, 2013; Woodward et al. 2011, 2015).
A second metric used to compare dust properties of comets is the ratio of the SED color temperature ($T_{\text{color}}$) to the temperature that solid spheres would have at a given heliocentric distance ($r_{\text{H}}$ (au)) in radiative equilibrium with the solar insolation, $T_{\text{BE}}(K) = 1.1 \times 278 (r_{\text{H}})^{-0.5}$ (see Hanner et al. 1997). At the epoch of the the SOFIA observations, the combined grism 6.0–36.5 μm SED can be fit with a single blackbody of temperature 239.5 ± 0.5 K, hence this ratio is ≈1.02. The enhanced color temperature over a graybody, which is expected for particles smaller than the wavelength, often is historically referred to as “superheat” $S$ (see Gehrz & Ney 1992). The silicate strength parameter is somewhat correlated with $S$ (Sitko et al. 2004; Woodward et al. 2015). For comet 67P/Churyumov–Gerasimenko, 1.15 ≤ $S$ ≤ 1.2, and $S$ is plotted along with the bolometric albedo at phase angle 90° (0.05–0.15) and the dust color (percent per 100 nm; Bockelée-Morvan et al. 2019). Comet C/2013 US10 (Catalina) has a smaller value for $S$ than comet 67P/Churyumov–Gerasimenko.

C/2013 US10 (Catalina) and 67P/Churyumov–Gerasimenko, both exhibiting a weak silicate feature and are carbon rich as determined from thermal modeling, provide a direct contradiction to older concepts commonly asserted in the literature. Commonly, many groups argued that some comets totally lacked silicate features because their solid grains were radiating as graybodies and not displaying resonances because the grains were so large that the grains themselves were optically thick (A’Hearn et al. 2005; Lisse et al. 2005). For comets with low dust production rates, estimation and subtraction of the nucleus’ contribution to the SED is important. When combined with higher sensitivity observations and subtraction of the nucleus flux density, thermal models that integrate over a size distribution of particles with composition-dependent dust temperatures shows that the comets with coma particles whose HGSD has $a_p$ ≤ 1 μm and that display weak silicate features are carbon rich.

### 3.4.1. The “Hot Crystal Model” and SOFIA in the Far-IR

The SOFIA spectrum has enhanced emission that rises near 36 μm but the observations do not extend to longer wavelengths to show a decline in flux density. Laboratory absorption spectra of powders of pure-Mg forsterite show that the absorbance is about equal at 33 μm and 11.1 μm (Koike et al. 2013), while the 19.5 and 23.5 μm features also have significant absorbance. The 33 μm emission from pure-Mg forsterite (Fo100) is not detected in the far-IR. The slope of the HGSD is well constrained by the SOFA data (given the low $\chi^2$).

The SOFIA data provide important constraints on the crystalline resonances in the far-IR and on the slope of the HGSD (Section 3.2.2). Our thermal models employ a “hot crystal model” for the temperatures for forsterite and enstatite, where their radiative equilibrium temperatures of crystals are increased by a factor of 1.9 ± 0.1 based on fitting the ISO SWS spectrum of comet C/1995 O1 (Hale–Bopp) (Harker et al. 2002). We speculate that hotter crystal temperatures may arise from crystals being in contact with other minerals that are more absorptive or from Fe metal inclusions such as “dusty olivines” (Kracher et al. 1984), or “relict” grains (Ruzicka et al. 2017).

### 3.5. Other Mineral Species Not Detected

Within our S/N in the SOFIA mid- to far-IR SED, neither hydrated phyllosilicates that have far-IR resonances distinct from anhydrous amorphous olivine and amorphous pyroxene nor the very broad 23 μm troilite (FeS, submicron sized; Keller et al. 2002) spectral signatures were seen (see Schambeau et al. 2015). Phyllosilicates, such as montmorillonite, as well as carbonates have absorptions in the 5–8 μm wavelength region (Roush et al. 1991; Crovisier & Bockelée-Morvan 2008), and neither of these compositions were detected in comet C/2013 US10 (Catalina).

### 3.6. The Search for Aliphatic and Aromatic Carbon

The BASS spectrum spans the 3.0–3.5 μm wavelength region where potentially the 3.28 μm peripheral hydrogen stretch on a ring carbon macromolecule (PAH), and the 3.4 μm –CH2, –CH3 aliphatic bonds arrangements that are prevalent in IDPs and Stardust materials (Matrajt et al. 2013) might be detectable. The analyses of a well-defined aliphatic carbon 3.4 μm band on the nucleus surface of 67P/Churyumov–Gerasimenko is presented by Raponi et al. (2020), and Rinaldi et al. (2019) also argue for the presence for this feature in coma observations. A broad 20% deep 3.2 μm features from organic ammonium salts also is discussed for the nucleus Poch et al. (2020). If the aliphatic material in comets is similar to that of IDPs then laboratory absorption spectra by Matrajt et al. (2005) of whole IDPs provide important information on the relative column densities of C atoms participating in different organic bonding groups including aliphatic bonds (–CH2, –CH3), aromatic (C=C), carbonyl, and carboxylic acid bonds in ketones, and ammonium salts.

Protopapa et al. (2018) point to the possible presence of an organic emission feature near 3.3 μm in higher spectral resolution observations of comet C/2013 US10 (Catalina) obtained on 2016 January 12 ($r_H = +1.3$ au) but do pursue any further detailed analyses. However, there are strong molecular ro-vibrational emission lines of C2H2 and CH2OH in the 3.28–3.5 μm region that significantly complicate deciphering underlying solid state organic features (Bockelée-Morvan et al. 1995; Dello Russo et al. 2006; Yang et al. 2009; Bockelée-Morvan et al. 2017a). Given these challenges, we do not report on detection of any aromatic or aliphatic features in the BASS.
data at our resolving power and sensitivity for comet C/2013 US$_{10}$ (Catalina). Thus, no spectral features were seen to indicate the presence of aromatic hydrocarbons (such as hydrogenated amorphous carbons (HACs), PAHs, a-C:H nanoparticles) or aliphatic carbons in the coma of C/2013 US$_{10}$ (Catalina).

Comet C/2013 US$_{10}$ (Catalina) has one of the few reported 5–8 μm wavelength spectrum from SOFIA (+FORCAST). We searched for spectral signatures of vibration modes of C=C bonds (6.25 μm = 1600 cm$^{-1}$), based on a constrained search of the observed absorption features in laboratory studies of cometary-like polyaromatic organics in IDPs (Matrajt et al. 2005) and in UCAMMs (Dartois et al. 2018) as well as asteroid insoluble organic materials (IOM; Alexander et al. 2017). The 6.25 μm C=C resonances are not dependent on the degree of hydrogenation; i.e., the number of peripheral hydrogen bonds compared to structural C=C bonds (Keller et al. 2004). The UCAMMS are mass dominated by organics, richer in N and poorer in O than cometary particles with probable origins in the outer protoplanetary disk (Dobrica et al. 2009). We also searched for C=O bonds (5.85 μm = 1710 cm$^{-1}$). There are tantalizing <3σ fluctuations near 1620 cm$^{-1}$ and 1510 cm$^{-1}$ that are in the regions of C=C stretching modes (see Table 2 of Merouane et al. 2014). However, the S/N is insufficient and the width of the fluctuations are narrow, narrower than the widths of the C=C resonances in the UCAMMs that have a preponderance of organics such that their features dominate the 5–8 μm region.

The lack of resonances from organics in the 5–8 μm wavelength region does not discourage us from further searches in cometary comae for these bonding structures with the much higher sensitivity provided by the James Webb Space Telescope ( JWST) and its instruments.

### 3.7. Carbon and Dark Particles

We find amorphous carbon dominates the composition of grain materials in comet C/2013 US$_{10}$ (Catalina). Dominance of carbon as a coma grain species was seen in other ecliptic comets including 103P/Hartley 2 (Harker et al. 2018) as well as the Oort cloud comets C/2007 N3 (Lulin) (Woodward et al. 2011) and C/2001 HT50 (Kelley et al. 2006). The outburst of dusty material from comet 67P/Churyumov-Gerasimenko at 1.3 au was carbon-only grains (with radii of order 0.1 μm), as measured by VIRTIS-H (Bardyn et al. 2017) and VIRTIS-M (Rinaldi et al. 2018) on Rosetta. Comets can exhibit changes in their silicate-to-carbon ratio between observation epochs, and notably, a few comets have had significant changes in their inner coma silicate-to-carbon ratios during a night’s observations (C/2001 Q4 (NEAT), Wooden et al. 2004; 103P/Hartley 2, Harker et al. 2018; 9P/Temple 1, Sugita et al. 2005; Harker et al. 2007).

Our cometary coma dust atomic C/Si ratios are calculated using a number of suppositions and should be taken as indicative values. Cometary atomic C/Si ratios are of interest for comparison with in situ studies of 67P/Churyumov–Gerasimenko and 1P/Halley and of laboratory investigations of IDPs and UCAMMs. The IDPs and UCAMMs are extraterrestrial materials likely to have originated from primitive bodies like comets and Kuiper-belt objects (KBOs), respectively (Bergin et al. 2015; Dartois et al. 2018; Burkhardt et al. 2019, and references therein). We choose to compare the C/Si of the submicron grain component determined from thermal models with bulk elemental composition measurements of IDPs (X-ray measurements). We elect to not compare C/Si ratios derived from resonances (aliphatic 3.4 μm, aromatic 6.2 μm, and other bands in UCAMMs) because in laboratory baseline-corrected absorption spectra, the amorphous carbon component would not be assessed because it does not have a resonance.

#### 3.7.1. Endemic Carbonaceous Matter in Comets

A dark refractory carbonaceous material darkens and reddens the surface of the nucleus of 67P/Churyumov–Gerasimenko, the surface material also displays a 3.4 μm feature (Raponi et al. 2020), and a similar aliphatic feature is suggested to exist in the coma of 67P/Churyumov–Gerasimenko (Rinaldi et al. 2017). We posit that the optical properties of amorphous carbon are representing well the dark refractory carbonaceous dust component observed in cometary comae through IR spectroscopy. Likely this dark refractory carbonaceous material is endemic to the comet’s surface. Cosmic rays of a few 10 keV only damage a thin veneer of hundreds of nanometer thickness (Strazzulla et al. 2003; Moroz et al. 2004; Quirico et al. 2016). This damage affects the structure (amorphization) and the composition (destruction of C–H and O–H bonds by dehydrogenation) of the materials (Moroz et al. 2004; Lantz et al. 2015; Quirico et al. 2016). Typical particle radii on the nucleus surface of 67P/Churyumov–Gerasimenko are at least tens of microns based on the observed red color of the surface at visible wavelengths (Jost et al. 2017), so cosmic rays do not damage the full particle volume. For example, IDPs studied by IR spectra indicate aliphatic bonds in particle interiors (Matrajt et al. 2005, 2013; Flynn et al. 2015) but a lack of organic bonds in their near surfaces, possibly due to damaging ultraviolet light and particle radiation in space (Flynn et al. 2004). Lastly, if the redeposition timescales for particles lofted from the nucleus but not escaping its gravity are about the orbital period of comet 67P/Churyumov–Gerasimenko (Marschall et al. 2020), then the ion irradiation timescales on the surface, which have been shown to amorphize carbon bonds or damage silicates, are too short by orders of magnitude (Baratta et al. 2004; Brunetto et al. 2014; Quirico et al. 2016).

However, the surface properties of the DN comet like C/2103 US$_{10}$ (Catalina) may differ from a Jupiter-family comet like 67P/Churyumov–Gerasimenko. A photon penetration depth of 1 μm for cosmic rays can induce chemical changes, such as development of an organic crust due to the conversion of low molecular weight hydrocarbons into a web of bound molecular species, from electronic ionization in dose time per 100 eV per 16 amu (H$_2$O) in the local ISM, which is a harsher environment than within the heliopause at ∼85 au (see the discussion in Strazzulla et al. 2003). Comet C/2013 US$_{10}$ (Catalina) may have had a radiation-damaged dust rime of up to a few centimeter depth, but DN comets can have their onset of activity at large heliocentric distances (Meech et al. 2009), where this material is likely shed when the comet’s activity first turns on. Thus, the amorphous carbon is not from a radiation rime because of the insufficient volume of the nucleus that can be altered by radiation compared to the mass loss pre-perihelion. Coupled with the arguments about insufficient timescales for materials recently exposed on cometary surfaces from either erosion or redeposition to be space weathered, we assert that the amorphous carbon that is in the observed coma of comet C/2013 US$_{10}$ (Catalina) is carbonaceous matter.
endemic to the comet nucleus. Moreover, the fluence and timescales or temperatures that change carbon-bonding structures typically are not reached in cometary coma. The material is refractory and stable. The dark refractory carbonaceous matter that is modeled with the optical constants of amorphous carbon (see Section 3.2.1) is endemic to comets. By the ubiquitous detection of a warm particle component in all cometary IR spectra observed to date, the carbonaceous matter is endemic to comets in general.

If dark refractory carbonaceous matter is stable on the surface, then this implies the matter will be stable in the coma, unless the temperatures are raised significantly. For example, if the size distribution significantly changes to smaller sizes, the latter would occur. Laboratory experiments demonstrate that amorphous carbon becomes graphitized at ∼3000 K (De Gregorio et al. 2017). Coma dust temperatures remain at ≤400 K dust compositions and particle sizes near 1 μm for comets near 1 au. The exception will be Sun grazers that come close to or enter the solar corona. On the other hand, aliphatic carbon may survive temperatures as high as 2001 Q4; and in two IDPs (L2021C5, L2021Q3), where its close proximity to other bonding structures is discussed respectively by Brunetto et al. (2014) and (L2021Q3; Merouane et al. 2016). Graphite can be formed at high temperatures (∼3273 K) although there are lower temperature processes that form graphite (Wirick et al. 2009). Ion bombardment of amorphous carbon is a competing process between amorphization and graphitization and this process depends on the structure of the starting amorphous carbon (Brunetto et al. 2011). Raman spectroscopy of one IDP shows “localized micrometer-scale distributions of extremely disordered and ordered carbons” (Brunetto et al. 2011).

In summary, cometary carbonaceous matter is macromolecular (De Gregorio et al. 2017) and not strictly aromatic (containing aromatic bonds), which is in contrast to meteoritic IOM (Alexander et al. 2007), as well as highly variable in composition and structure.

3.9. Cometary Coma Elemental C/Si Ratios

In the following discussion, we investigate the plausible implications of the cometary coma thermal model’s relative mass fractions (i.e., the mass fraction of amorphous carbon to the mass fractions of the amorphous and crystalline silicates) on the elemental abundance ratio of C/Si. We compare the inferred elemental ratio C/Si for comet C/2013 US10 (Catalina) from thermal models to the C/Si ratio determined for IDPs using scanning electronic microscopy with energy dispersive X-ray analysis (the SEM-EDX method; Thomas et al. 1993b), and by mass spectrometry for comet 1P/Halley and comet 67P/Churyumov-Gerasimenko (COSIMA).

We will show that the relative mass fractions of C/Si derived from our thermal models of comet C/2013 US10 (Catalina) and a handful of other recently observed and modeled comets are consistent with the average C/Si = 5.5±1.5, derived by COSMIA for thirty 67P/Churyumov-Gerasimenko particles (Bardyn et al. 2017), for 1P/Halley particles measured by Vega-1 and Vega-2 mass spectrometers during spacecraft encounters, and also for the upper range of C/Si for IDPs (see Bergin et al. 2015). The enigmatic comet C/1995 O1 (Hale–Bopp), with its preponderance of submicron crystalline silicates (Harker et al. 2002), also is included in our analysis to demonstrate its lower C/Si ratio that is in the lower range of the IDP C/Si ratios (Bardyn et al. 2017) and
also close to the range determined for CI chondrites (Bergin et al. 2015).

Our cometary coma dust C/Si atomic ratios are calculated using a few suppositions and should be taken as indicative values, which are of interest for comparison with in situ studies of 67P/Churyumov–Gerasimenko and 1P/Halley and of laboratory investigations of IDPs and UCAMMs (Matrajt et al. 2005; Brunetto et al. 2014; Bardin et al. 2017; Dartois et al. 2018). The IDPs and UCAMMs are extraterrestrial materials likely to have originated from primitive bodies like comets and KBOs, respectively (Dobrica et al. 2009 and references therein). Unlike laboratory measurements of IDPs, micrometeorite samples, or Stardust particles, which generally are the measure of single grains or isolated domains within a matrix, values returned from remote-sensing spectroscopic observations represent a coma-wide measure from a large ensemble of thermally radiating dust particles of various radii.

Our suppositions in deriving C/Si atomic ratios are as follows: (a) amorphous carbon is a good optical analog for dark highly absorbing carbonaceous matter in cometary comae and (b) thermal model relative mass fractions derived for amorphous carbon represent a significant fraction of the carbonaceous matter in the coma (Section 3.9.1).

### 3.9.1. Counting Carbon Atoms

We are comparing the C/Si atomic ratio derived for cometary samples using different techniques. Mass spectroscopy directly measures the elemental C/Si ratio, which is the method for in situ measurements. However, nondestructive techniques that allow counting the carbon atoms in IDPs or Stardust samples depend on the experimental method. X-ray SEM-EDX techniques (Thomas et al. 1993b) can count all of the carbon atoms whereas IR absorption spectroscopy counts the carbon atoms involved in the observed resonances. Laboratory IR absorption spectroscopy measures the C/Si by converting the integrated band strengths into the number of atoms for aliphatic and/or aromatic bands compared to the 10 \( \mu \text{m} \) silicate band (Matrajt et al. 2005; Brunetto et al. 2014). Laboratory absorbance spectroscopy fits and subtracts a spline baseline to yield a linear baseline for the purpose of integrating the observed band strengths (see Matrajt et al. 2005). Amorphous carbon is not observed in absorbance in spectroscopy of IDPs because amorphous carbon lacks spectral resonances. To make a comparison between cometary C/Si derived from thermal models of amorphous carbon and C/Si derived from laboratory measurements and in situ measurements, we choose to employ the SEM-EDX measurements that are counting the carbon atoms but not discerning the carbon-bonding structures.

Currently, we cannot claim knowledge of aliphatic and aromatic content in comet coma dust populations of multiple comets via IR spectroscopy. If we cannot detect signatures of these bonding structures, we cannot definitely determine their contribution to the observed emission. However, we can use IDPs to indicate what the potential increase in C/Si might be if the aliphatic or aromatic bonds were spectroscopically detected.

We can examine what C/Si atomic ratios are derived from organic features in laboratory absorbance spectra of IDPs and compare to the C/Si derived for comets using thermal modeling of the warm particle component that is modeled with amorphous carbon. Many IDPs show the aliphatic 3.4 \( \mu \text{m} \) feature. The 3.4 \( \mu \text{m} \) feature is composed of the aliphatic CH\(_3\) symmetric vibration (at \( \sim 2850 \text{ cm}^{-1} \)), the CH\(_2\) asymmetric vibration (at \( \sim 2922 \text{ cm}^{-1} \)) and the weaker CH\(_3\) asymmetric vibration (at \( \sim 2958 \text{ cm}^{-1} \)) as discussed in Matrajt et al. (2005). In six IDPs, the 3.4 \( \mu \text{m} \) aliphatic carbon features yield 0.27 \( \leq \) C/Si \( \leq 1.4 \) with a mean C/Si = 0.55 \( \pm 0.43 \) (see Table 4 of Matrajt et al. 2005). For three out of the six IDPs, acid dissolution of the silicates allowed the detection of the intrinsically weaker aromatic skeletal ring stretch C–C at 6.25 \( \mu \text{m} \) (1600 cm\(^{-1}\)), which raises the atomic ratios for these three IDPs from C\(_{\text{aliphatic}}\)/Si = 0.78, 0.11, 0.55 to C\(_{\text{aliphatic}+\text{aromatic}}\)/Si = \{19.4, 3.1, 5.1\} (see Table 5 of Matrajt et al. 2005).

Most IDPs, however, do not possess an aromatic 3.28 \( \mu \text{m} \) feature from C–H peripheral bonds on C=C skeletal rings. Keller et al. (2004) suggest the lack of the 3.28 \( \mu \text{m} \) aromatic feature is due to “much of the carbonaceous matter is comprised [of] very poorly graphitized carbon, possessing only short range order (<2 nm) or very large PAH molecules.” The C=C bonds are better tracers of the aromatics than the peripheral C–H bonds. As yet, no comet has been observed with organic features that are of comparable absorbance to the silicate features as observed in absorption spectra of three UCAMMs, where organic absorbances are as strong as for the silicate features (Dartois et al. 2018). As other authors suggest, we infer that comets have less “outer disk processed organics” than UCAMMs. This conjecture is also supported by noting the ratio of nitrogen to carbon (N/C) in 67P/Churyumov–Gerasimenko is less than the N/C in UCAMMs (Bardin et al. 2017; Dartois et al. 2018). If IR spectra of cometary coma were to detect the 3.4 \( \mu \text{m} \) feature at about the same contrast to the silicate feature as in laboratory absorbance spectra of IDPs (Matrajt et al. 2005; Brunetto et al. 2014; Merouane et al. 2016), then we may infer that the C/Si for our comets that we analyze might increase \( \sim 20\% \).

### 3.9.2. The C/Si Gradient in the Solar System

We derived the C/Si atomic ratio using the thermal model dust compositions (and relevant atomic amu) described in Section 3.3 and the relative masses of the submicron grains for each composition returned from the best-fit thermal model. The asymmetric uncertainties in the relative masses derived from the thermal models were “symmetrized” following the description discussed by (Method#2, Audi et al. 2017), cognizant of the limitations of this approach (see Barlow 2003; Possolo et al. 2019) to enable standard error propagation techniques. The carbon-to-silicon atomic ratio is defined as

\[
\frac{C}{Si} = \frac{\Sigma(C_{\text{species}})}{\Sigma(Si_{\text{species}})} = \frac{N_{p}(C) \cdot C_{\text{amu}}}{N_{p}(Si) \cdot Si_{\text{amu}}} = \frac{N_{p}(A) \cdot A_{amu} + N_{p}(AP) \cdot AP_{amu} + N_{p}(CO) \cdot CO_{amu} + N_{p}(CP) \cdot CP_{amu}}{N_{p}(Si) \cdot Si_{amu}} \quad (1)
\]

where

\[
\alpha = \frac{0.5 \cdot Mg_{\text{amu}} + 0.5 \cdot Fe_{\text{amu}}}{Si_{\text{amu}}} \times 2 + Si_{\text{amu}} + 4 \cdot O_{\text{amu}}
\]

\[
\beta = \frac{0.5 \cdot Mg_{\text{amu}} + 0.5 \cdot Fe_{\text{amu}}}{Si_{\text{amu}}} + Si_{\text{amu}} + 3 \cdot O_{\text{amu}}
\]

\[
\gamma = \frac{(Mg_{\text{amu}}) \times 2}{Si_{\text{amu}}} + Si_{\text{amu}} + 3 \cdot O_{\text{amu}}
\]

\[
\delta = \frac{(Mg_{\text{amu}}) \times 2}{Si_{\text{amu}}} + Si_{\text{amu}} + 4 \cdot O_{\text{amu}}
\]

See Table 5 of Matrajt et al. (2005).
Carbon-depletion gradient with complex chemical networks

are the $\alpha$, $\beta$, $\gamma$, and $\delta$ are the number of Si atoms per unit mass, and the values for $N_p$ (the number of grains at the peak $[\alpha]_p$ of the HGSD) are found in Table 3. Table 4 summarizes the derived C/Si atomic ratios for comet C/2013 US$_{10}$ (Catalina) and other comets observed with SOFIA (+FORCAST) as well as comet C/1995 O1 (Hale–Bopp) (Harker et al. 2002). The C/Si atomic ratio for the comets in Table 4, UCAMMs (data from Dartois et al. 2018), and IDPs and other comets (data from Bergin et al. 2015) are presented in Figure 8. Recent measurements of solar cosmic abundances create an upper limit for the ISM C/Si of 10 as discussed in Dartois et al. (2018 and references therein). UCAMMs are above the solar cosmic abundance limit. Thus, those who study UCAMMs suggest that the organics have sequestered carbon from the gas phase and converted it to a solid phase in the cold outer disk or on the surfaces of nitrogen-rich cold body surfaces because of their enhanced N/C ratios (Dartois et al. 2013, 2018). As measured or computed, cometary coma appear to lack the high C/Si ratios of UCAMMs.

Comets by their C/Si appear to be sampling similar abundances of carbon in the optically active composition of coma particles as SEM-EDX-derived C/Si ratios are measuring for IDPs. Many, but not all, comets have C/Si commensurate with IDPs, and IDPs are more carbon rich than carbonaceous chondrites (Figure 8). Two Sun-grazing comets from the Kreutz family of comets, C/2003 K7 and C/2011 W3 (Lovejoy), have silicate-rich dust and fall in the carbonaceous chondrites (CC) range (Caravella et al. 2010; McCauley et al. 2013; Bergin et al. 2015).

Dartois et al. (2013, 2018), Gail & Trieloff (2017), and other authors suggest that there was a carbon gradient in the early solar system. The comet C/Si values support this contention of gradient in the carbon with heliocentric distance of formation (see Rubin et al. 2019). Commensurate with these results, CONSERT on Rosetta/Philae suggest comets are a large carbon reservoir given the nucleus’ permittivity and density constraints on the dust composition in the nucleus (Herique et al. 2016), which agrees within uncertainties with the average specific density of dust particles in the comet C/2013 US$_{10}$ (Catalina)’s coma. The existence of a carbon gradient in solar systems also is bolstered by the C/Si ratios of IDPs.

Destruction of carbon occurred in the inner disk, which is the long-standing “carbon deficit problem” (Lee et al. 2010; Bergin et al. 2015). Disk modelers are working to predict the carbon-depletion gradient with complex chemical networks (Wei et al. 2019). Another model investigates the removal of carbon through oxidation and photolysis when particles are transported to the exposed upper disk layers but radial transport erases signatures unless other mechanisms quickly destroy carbon, like flash heating from FU Ori outbursts, or mechanisms preventing replenishment of the inner disk, such as sustained particle drift barrier, i.e., a gap opened by the formation of a giant planet. Klarmann et al. (2018) argued that “a sustained drift barrier or strongly reduced radial grain mobility is necessary to prevent replenishment of carbon from the outer disk [to the inner disk].”

Heat and/or high oxygen fugacity conditions in the inner protoplanetary disk can convert carbon from its incorporation in refractory particles to carbon in gas-phase CO or CO$_2$. As discussed (Section 3.7.1), particle temperatures above $\sim$823 K can destroy aliphatic carbon. Flash heating of Mg–Fe silicates

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### Table 4

| Comet              | Telescope/Instrument  | C/Si          | (References) |
|--------------------|-----------------------|---------------|--------------|
| C/2013 US10 (Catalina) | IRTF (+BASS)         | 4.180 ± 0.308 | (1)          |
| C/2013 US10 (Catalina) | SOFIA (+FORCAST)     | 6.556 ± 3.262 | (1)          |
| C/2013 K1 (Pan-STARRS) | SOFIA (+FORCAST)     | 3.841 ± 1.086 | (2)          |
| C/2013 X1 (Pan-STARRS) | SOFIA (+FORCAST)     | 7.781 ± 6.091 | (3)          |
| C/2018 W2 (Africano)   | SOFIA (+FORCAST)     | 6.204 ± 3.858 | (3)          |
| C/1995 O1 (Hale–Bopp)  | IRTF (+HIFOGS)       | 0.420 ± 0.001 | (4)          |

Note. Computed from relative mass ratios of thermal model dust composition components, adopting an amorphous carbon density $\rho = 1.5 \, \text{g cm}^{-3}$. The Appendix provides the complete model in Tables 6–9, including the revision to the C/2013 K1 (Pan-STARRS) and C/1995 O1 (Hale–Bopp) models resulting from an amorphous carbon specific density $\rho_{\text{ACar}} = 1.5 \, \text{g cm}^{-3}$.

**References.** (1) This work. (2) Woodward et al. (2015). (3) C. E. Woodward et al. (2021, in preparation). (4) Harker et al. (2002).
in the presence of carbon is a possible formation pathway for Type I chondrules (Connolly et al. 1994). If cometary particles can drift interior to the water evaporation front, then cometary materials may deliver carbon to the inner protoplanetary disk. Delivery of carbon to the gas phase of the inner disk by cometary grain requires inward delivery mechanisms during the early pebble accretion phase of disk evolution when the motions of aggregating materials are dominated by inward pebble drift (Misener et al. 2019; Andrews 2020). Such delivery requires that amorphous carbon particles already be incorporated into cometary grains in addition to the need that the sublimation temperature of amorphous carbon be higher than water ice so that the delivery of carbon particles is interior enough for carbon to become enhanced in the gas phase. High carbon abundances in the gas phase are required to explain the poorly graphitized carbon (PGC) halos around Fe cores in two terminal Stardust particles (Wirick et al. 2009; De Gregorio et al. 2017).

Earth’s bulk C/Si atomic ratio is much smaller and models for its core formation and evolution assume a carbonaceous chondrite supply of carbon was available to form Earth (Bergin et al. 2015). Cometary C/Si atomic ratios are much higher than carbonaceous chondrites. The outer disk was richer in carbon than the inner disk. The carbon gradient may be another indication of planetary gaps sculpting the compositions of small bodies. Burkhart et al. (2019) hypothesize that the isotope variances of planetary bodies, traced through meteoritic and IDPs, can be explained if there were isotopically distinct nebular reservoirs of noncarbonaceous and carbonaceous chondrites that were not fully mixed in the primordial disk of the solar system. A planetary gap created by Jupiter’s formation which inhibited mixing between the inner and outer disk could also explain the dichotomy in between noncarbonaceous and carbonaceous meteorites (Nanne et al. 2019).

Cometary C/Si atomic ratios highlight the “carbon deficit” that occurred in the inner disk and the dichotomy between the inner and outer disk when juxtaposed with the C/Si atomic ratios found for Earth and ordinary chondrites. Furthermore, the dust composition of many comets demonstrates a carbon-rich reservoir existed in the regimes of comet formation that are pertinent to the understanding the evolution of our protoplanetary disk and the formation of the planets.

3.10. Dust Production Rates

The optical spectra of comets in the i′ band tends to be dominated by dust. However, red CN gas emission bands, CN(2,0) and CN(3,1), can be present at redder wavelengths within the i′ band (Swings 1956; Fink et al. 1991; Cochran et al. 2015). The presence of these emission lines may contaminate measurements of the scattered-light dust continuum surface brightness and hence estimates of the dust production rate. Optical spectra of comet C/2013 US10 (Catalina) obtained on 2015 December 18 (Kwon et al. 2017) show weak CN(2,0) and CN(3,1) band emission. However, optical spectra obtained after the epoch of the MORIS and FPI+ imagery in 2016 March 18 show no strong emission features redward of 7630 Å that contribute to the i′-band long-wavelength cutoff (Hyland et al. 2019). The azimuthally averaged radial profiles of comet C/2013 US10 (Catalina) derived from the MORIS and FPI+ imagery, presented in Figure 9, show little deviation from a 1/ρ profile (Gehrz & Ney 1992) at large cometocentric distances consistent with a steady-state coma without significant CN contamination.

Application of standard comet image enhancement techniques to these optical data (see Samarasinha & Larson 2014; Samarasinha et al. 2014) reveals no structures in the coma such as jets or spirals at this epoch.

The dust production rate of comet C/2013 US10 (Catalina) during the epoch of the BASS observations (2016 January 10.633 UT) was derived using the proxy quantity Af i (A’Hearn et al. 1984). When the cometary coma is in steady state, this aperture-independent quantity can be parameterized as

\[ A(\theta)f_{i} = \frac{4r_{h}^{2}}{\rho} \left( \Delta \text{cm} \right)^{2} 10^{-0.4\left(m_{\text{comet}}-m_{\odot}\right)} \text{cm}. \]  

In this relation, A(θ) is four times the geometric albedo at a phase angle θ, f is the filling factor of the coma, m_{comet} is the measured cometary magnitude, and Δ(cm) are the heliocentric and geocentric distances, respectively. The Halley–Marcus (HM; Schleicher et al. 1998; Marcus 2007a, 2007b) phase angle correction^{13} was used to normalize A(θ)f i to a 0° phase angle, wherein we adopted an interpolated value of HM = 0.3424 and 0.3946 commensurate with the epoch of our optical observations on 2016 January 11.63 UT and 2016 February 9.34 UT, respectively. Table 5 reports values of A(0°)f i = (A(θ)f i /HM) at a selection of aperture sizes (distances from the comet photocenter) in the i′ band. The dust production rate is similar to that observed in other moderately active comets, such as C/2012 K1 (Pan-STARRS) discussed by Woodward et al. (2015).

We can roughly estimate the dust mass-loss rate by taking the mass of dust observed in the coma inside of our aperture as the 1/ρ dependence of the surface brightness distribution indicates a steady-state coma. If we adopt for the outflow velocity of 100 μm radii and larger particles which carry most of the mass a value of v_{dust} ≈ 20 m s⁻¹ (Rinaldi et al. 2018) and assume a steady outflow of material through a spherical bubble at some distance R (meters) near the nucleus surface, the mass-loss rate can be estimated as

\[ M_{\text{dust}} \approx \frac{3 \cdot M_{\text{dust}} \times v_{\text{dust}}}{R}, \]  

where M_{dust} has units of g s⁻¹. If the nucleus of comet C/2013 US10 (Catalina) is comparable in size to that typically inferred for many comets, 1.5 km, then M_{dust} ≈ 4 × 10⁻³ M_{dust} [v_{dust}/20(m/s)]. At 1.7 au, when M_{dust} = 4 × 10⁸ g (Table 3), then M_{dust} ≈ 1.6 × 10⁶ g s⁻¹.

Fink & Rubin (2012) discuss how the A(θ)f i can be tied to the mass production rate, given the HGSD parameters, computing dust mass-loss rate (in kg s⁻¹) by assuming a particle density of 1 g cm⁻³ for various particle size distribution functions. Taking an average value of N = 3.5, corresponding to da/da ∼ a⁻³.5 which yielded a mass-loss rate of 22.8 k s⁻¹ from the detailed computations of Fink & Rubin (2012; see Table 2) and using Af i at zero phase for C/2013 US10 (Catalina) of ~6290 cm (Table 5), one finds M_{dust} ≈ 2.4 × 10⁶ g s⁻¹. This is comparable to our latter estimate.

^{13} http://classic.sdsu.edu/dr5/algorithms/sdsuUBVRITransform.html#vega_Sun_colors
^{14} http://asteroid.lowell.edu/comet/dustphase.html
If we assume the density of the nucleus, which is a porous dust–ice mixture, is \( \rho_{\text{mac}} \sim 1 \text{ g cm}^{-3} \) (Fulle et al. 2019), then a rough estimate of the surface erosion rate from the nucleus of comet C/2013 US\(_{10}\) (Catalina) is \( \sim 1 \text{ mm day}^{-1} \) if the entire surface is active and if the radius of the comet is \( \sim 1.5 \text{ km} \). The depth of space weathering of a DN comet in the local ISM might be at most a centimeter over the age of the solar system, and this material would be shed in a timeframe of \( \lesssim 2 \text{ weeks} \) at the observed dust mass-loss rate, which we have translated to an erosion rate. For perspective, cumulative erosion depths for comet 67P/Churyumov–Gerasimenko depended on the nucleus geography and solar insolation, and from the start of the Rosetta mission until the first equinox were 6 mm–0.1 m and to the end of the mission were of order 0.3–4 m (Combi et al. 2020).

The quantity \( \epsilon f \rho \) (see Appendix A of Kelley et al. 2013), a parameter which is the thermal emission corollary of the scattered light, the light-based \( A f \rho \) was also computed using our

**FORCAST broadband photometry.** \( \epsilon f \rho \) is defined as

\[
\epsilon f \rho = \frac{\lambda^4 F_\nu}{\pi \rho B_\nu} \quad \text{(cm)},
\]

where \( \epsilon \) is the effective dust emissivity, \( F_\nu \) is the flux density (Jansky) of the comet within the aperture of radius \( \rho \), \( B_\nu \) is the Planck function (Jy sr\(^{-1}\)) evaluated at the temperature \( T_c = \frac{f_{\text{bb}}}{f_{\text{bb}} - 0.5} \approx 323.9 \text{ K} \), where \( T_c \) is the color temperature. Derived values of \( \epsilon f \rho \) for comet C/2013 US\(_{10}\) (Catalina) from SOFIA photometry are presented in Table 2.

### 3.11. Dust Bolometric Albedo

Our near-simultaneous optical observations conducted on the same night as our measurement of the infrared SED of comet C/2013 US\(_{10}\) (Catalina) enable us to estimate the bolometric dust albedo as described by Woodward et al. (2015). The measured albedo depends on both the composition and structure of the dust grains as well as the phase angle (Sun–comet observer angle) of the observations. As the grain albedo is the ratio of the scattered light to the total incident radiation, the thermal emission at IR wavelengths and the scattered-light component observed at optical wavelengths are linked through this parameter.

The photometry from the \( \iota' \) imagery in an equivalent aperture that corresponds to the apertures used to measure the IR SEDs provides an estimate of \( A f \rho_{\lambda, \text{max}}^{\text{scattering}} \). An estimate of \( [\lambda F_\lambda]_{\text{max}}^{\text{scattering}} \) is obtained from a filter-integrated equivalent photometric point at 10 \( \mu \text{m} \) derived by integrating with the observed IR SED over the bandwidth of the FORCAST F111 filter. We find that the coma of comet Oort cloud C/2013 US\(_{10}\) (Catalina) has a low bolometric dust albedo, \( \epsilon f \rho \), of \( \lesssim 5.1\% \pm 0.1\% \) at a phase angle of 47°80 to \( \pm 13.8\% \pm 0.5\% \) at a phase angle of 33°01.

Figure 10 shows the derived \( \epsilon f \rho \) as a function of phase angle, \( \theta \), for a variety of comets, where the red stars denoted the values for C/2013 US\(_{10}\) (Catalina). At 1.3 au, the bolometric albedo of comet C/2013 US\(_{10}\) (Catalina) is likely measuring the reflectance properties of the refractory particles because ice grains have very short lifetimes at this heliocentric distance (Beer et al. 2006; Protopapa et al. 2018). The reflectance of individual refractory particles from the coma of comet 67P/Churyumov–Gerasimenko as measured by Rosetta COSIMA/Cosiope is from 3% to 22% at 650 nm (Langvin et al. 2017, 2020), which spans the range of bolometric albedos measured for comet comae.
infrared spectral features compared to interplanetary dust particles, chondritic materials, and Stardust samples suggest that the dark carbonaceous material is well represented by the optical properties of amorphous carbon. We argue that this dark material is endemic to comets.

The C/Si atomic ratio of comets in context with that derived from studies of interplanetary dust particles, micrometeorites, and Stardust samples suggest that a carbon gradient was present in the early solar nebula. As we observe more comets, and especially take the opportunities to observe dynamically new comets with SOFIA, the James Webb Space Telescope and other capabilities, a significant subset of comets that are carbon rich likely will arise, providing important constraints on newly proposed interpretations of disk processing in the primitive solar system.

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Facilities: NASA SOFIA (FORCAST/FPI+), NASA IRTF (BASS/MORIS).
Software: IRAF (Tody 1986, 1993), IDL, JPL Horizons (Giorgini et al. 1996), Aperture Photometry Tool (APT) Laher et al. (2012).

Appendix
Tables of Revised Thermal Models

As described in the text (Section 3.2.6), we have adopted a value for 1.5 g cm$^{-3}$ for the specific density of amorphous carbon, $\rho_s$(ACar), in our thermal models. In early work, we employed a higher specific density of 2.5 g cm$^{-3}$. In order to compare the atomic carbon-to-silicate ratios consistently, thermal models for all SOFIA-observed comets included in this analysis were modeled or remodeled with a common value of $\rho_s$(ACar) = 1.5 g cm$^{-3}$. Tables 6–9 for comets C/2012 K1 (Pan-Starrs) (see Woodward et al. 2015), C/1995 O1 (Hale–Bopp) (see Harker et al. 2002), and C/2013 X1 (Pan-STARRS) and C/2018 W2 (Africano) (C. E. Woodward et al. 2020, in preparation) are given for completeness.

4. Conclusion

Mid-IR 6.0 $\lesssim \lambda(\mu m) \lesssim$ 40 spectrophotometric observations of comet C/2013 US$_{10}$ (Catalina) at two temporal epochs yielded an inventory of the refractory materials in the comet’s coma and their physical characteristics through thermal modeling analysis. The coma of C/2013 US$_{10}$ (Catalina) has a high abundance of submicron-radius, moderately porous (fractal porosity $D = 2.727$) carbonaceous amorphous grains with a silicate-to-carbon mass ratio $\lesssim$0.9. This comet also exhibited a weak 10 $\mu$m silicate feature.

Comet C/2013 US$_{10}$ (Catalina) is an example of a subset of comets with weak silicate features that are definitively shown to have low silicate-to-carbon ratios for the submicron grain component (as deduced from thermal model analysis of the SEDs), that is, they are carbon rich. Their thermal emission is dominated by warmer particles that are significantly more absorbing at UV to near-IR wavelengths than silicates. The spectral grasp of SOFIA (+FORCAST) provided a constraint that required the presence of amorphous carbon as a dominate constituent of the coma particle population (submicron dust) as silicate particles cannot provide the lack of contrast above blackbody emission at far-infrared wavelengths. The surface area of the thermal emission is dominated by the smaller grains and for the silicates, the smaller crystalline forsterite grains that produce resonances at 19.5, 23.5, and 27.5 $\mu$m are not evident in the spectrum of comet C/2013 US$_{10}$ (Catalina), which is a puzzle.

A dark refractory carbonaceous material darkens and reddens the surface of the nucleus of 67P/Churyumov–Gerasimenko. Comet C/2013 US$_{10}$ (Catalina) is carbon rich. Analysis of comet C/2013 US$_{10}$ (Catalina)’s grain composition and observed
### Table 6
Derived Grain Composition of Comet C/2012 K1 (Pan-STARRS)\(^a\)

| Dust Components                      | Relative Mass Grains | \((N_p \times 10^{20})\) |
|--------------------------------------|----------------------|---------------------------|
| Amorphous pyroxene                  | 0.658\(\pm\)0.084   | 0.398\(\pm\)0.077 \(\times 10^7\) |
| Amorphous olivine                    | 0.000\(\pm\)0.085   | 0.000                     |
| Amorphous carbon                     | 1.656\(\pm\)0.056   | 0.455\(\pm\)0.064         |
| Crystalline olivine                  | 0.181\(\pm\)0.161   | 0.147\(\pm\)0.104         |
| Crystalline pyroxene                 | 0.000                | 0.000                     |

| Resultants                           |                      |                           |
|--------------------------------------|----------------------|---------------------------|
| Total mass submicron grains \((gm) \times 10^6\) | 3.727\(\pm\)0.426   |                           |
| Amorphous silicate dust fraction     | 0.398\(\pm\)0.080   |                           |
| Crystalline silicate dust fraction   | 0.147\(\pm\)0.104   |                           |
| Silicate-to-carbon ratio\(^d\)       | 1.198\(\pm\)0.271   |                           |
| Crystalline silicate mass to total silicate mass\(^e\) | 0.270\(\pm\)0.160   |                           |
| \(\alpha_p(\mu m)\)\(^f\)           | 0.7                  |                           |
| Fractal porosity \((D)\)             | 2.857                |                           |

| Other Parameters                     |                      |                           |
|--------------------------------------|----------------------|---------------------------|
| Hanner grain-size distribution M:N   | 22.2:3.7             |                           |
| Reduced \(\chi^2\)                   | 1.06                 |                           |
| Degrees of freedom                   | 146                  |                           |

**Notes.**

\(^a\) Uncertainties represent the 95% confidence level.

\(^b\) Comet on 2014 June 6 UT \(r_h = 1.70\) au, \(\Delta = 1.71\) au.

\(^c\) Number of grains, \(N_p\), at the peak \(\alpha_p\) of the Hanner grain-size distribution (HGSD).

\(^d\) Ratio represents the bulk mass properties of the materials in the models.

\(^e\) \(f_{cryst} \equiv m_{cryst}/(m_{amorphous} + m_{cryst})\), where \(m_{cryst}\) is the mass fraction of submicron crystals.

\(^f\) Peak grain size (radius) of the HGSD.
Table 7
Derived Grain Composition of Comet C/2013 X1 (Pan-STARRS)*

| SOFIA (+FORCAST)* | Relative Mass Submicron Grains | Thermal Model SED Details | \((N_p \times 10^{20})^f\) |
|-------------------|--------------------------------|--------------------------|-----------------------------|
| Dust Components   |                                |                          |                             |
| Amorphous pyroxene| 0.000±1.000 ±0.000 ±1.000     | 0.000±1.000 ±0.000 ±1.000 |
| Amorphous olivine | 0.213±1.019 ±0.001 ±1.000     | 0.214±1.019 ±0.001 ±1.000 |
| Amorphous carbon  | 1.197±0.064 ±0.004 ±0.004     | 0.545±0.149 ±0.004 ±0.004 |
| Crystalline olivine| 0.138±0.212 ±0.001 ±0.001    | 0.241±0.213 ±0.001 ±0.001 |
| Crystalline pyroxene| 0.643±0.004 ±0.004 ±0.004  | 0.045±0.004 ±0.004 ±0.004 |
| Resultants        |                                |                          |                             |
| Total mass submicron grains (gm) \(\times 10^{6}\) | 1.567±0.358 ±0.153 ±0.153 | ...                        |
| Amorphous silicate dust fraction | 0.214±0.163 ±0.009 ±0.009    | ...                        |
| Crystalline silicate dust fraction | 0.241±0.213 ±0.001 ±0.001    | ...                        |
| Silicate-to-carbon ratio\(^d\) | 0.834±0.413 ±0.004 ±0.004    | ...                        |
| Crystalline silicate mass to total silicate mass\(^e\) | 0.530±0.260 ±0.030 ±0.030    | ...                        |
| \(a_p(\mu m)\)\(^f\) | 0.6                                | ...                        |
| Fractal porosity (D) | 2.727                                | ...                        |

Other Parameters
| Hanner grain-size distribution M:N | 18.5:3.7                        | ...                        |
| Reduced \(\chi^2\)                | 0.580 6                          | ...                        |
| Degrees of freedom                | 147                               | ...                        |

Notes.
\(^a\) Uncertainties represent the 95% confidence level.
\(^b\) Comet on 2016 July 13 UT \(r_h = 1.80\) au, \(\Delta = 1.02\) au.
\(^c\) Number of grains, \(N_p\), at the peak \(a_p\) of the Hanner grain-size distribution (HGSD).
\(^d\) Ratio represents the bulk mass properties of the materials in the models.
\(^e\) \(f_{\rm crys} \equiv m_{\text{cryt}}/[m_{\text{amorph}} + m_{\text{cryt}}]\), where \(m_{\text{cryt}}\) is the mass fraction of submicron crystals.
\(^f\) Peak grain size (radius) of the HGSD.
### Table 8
Derived Grain Composition of Comet C/2018 W2 (Africano)

| Thermal Model SED Details | \((N_p \times 10^{19})^c\) |
|---------------------------|-----------------------------|
| **Dust Components**       |                             |
| Amorphous pyroxene        | 0.166 ± 0.692               |
| Amorphous olivine         | 0.488 ± 0.294               |
| Amorphous carbon          | 0.308 ± 0.300               |
| Crystalline olivine       | 0.082 ± 0.340               |
| Crystalline pyroxene      | 0.000                       |
| **Resultants**            |                             |
| Total mass submicron grains (gm) \(\times 10^{18}\) | 0.006 ± 0.000 |
| Amorphous silicate dust fraction | 0.050 ± 0.005 |
| Crystalline silicate dust fraction | 0.000 ± 0.000 |
| Silicate-to-carbon ratio\(^d\) | 0.303 ± 0.122 |
| Crystalline silicate mass to total silicate mass\(^e\) | 0.050 ± 0.224 |
| \(a_p (\mu m)^f\)         | 0.4                         |
| Fractal porosity \((D)\)  | 2.857                       |
| **Other Parameters**      |                             |
| Hanner grain-size distribution M:N | 10.2:3.4 |
| Reduced \(\chi^2\)        | 0.84                        |
| Degrees of freedom        | 134                         |

|                | Relative Mass Submicron Grains |
|----------------|-------------------------------|
|                | \(2.698_{-0.334}^{+0.153} \times 10^7\) |

**Notes.**
- \(^a\) Uncertainties represent the 95\% confidence level.
- \(^b\) Comet on 2019 October 18 UT \(r_h = 1.60\) au, \(\Delta = 0.84\) au.
- \(^c\) Number of grains, \(N_p\), at the peak \(a_p\) of the Hanner grain-size distribution (HGSD).
- \(^d\) Ratio represents the bulk mass properties of the materials in the models.
- \(^e\) \(f_{\text{cryst}} \equiv m_{\text{cryst}} / [m_{\text{amorphous}} + m_{\text{cryst}}]\), where \(m_{\text{cryst}}\) is the mass fraction of submicron crystals.
- \(^f\) Peak grain size (radius) of the HGSD.
Table 9
Derived Grain Composition of Comet C/1995 O1 (Hale–Bopp)*

| Dust Components | (N_0 × 10^{22}) | Relative Mass Submicron Grains |
|-----------------|-----------------|-------------------------------|
| Amorphous pyroxene | 5.55 ± 0.009 | 0.304 ± 0.000 |
| Amorphous olivine  | 6.34 ± 0.005 | 0.34 ± 0.001 |
| Amorphous carbon   | 3.16 ± 0.002 | 0.079 ± 0.001 |
| Crystalline olivine| 3.18 ± 0.002 | 0.224 ± 0.000 |
| Crystalline pyroxene| 0.64 ± 0.004 | 0.046 ± 0.001 |

Residuals

| Parameter | Value |
|-----------|-------|
| Total mass sub-mm grains (gm) | 420.13 ± 0.000 |
| Amorphous silicate dust fraction | 0.65 ± 0.001 |
| Crystalline silicate dust fraction | 0.27 ± 0.001 |
| Silicate-to-carbon ratio | 11.67 ± 0.008 |
| Crystalline silicate mass to total silicate mass | 0.29 ± 0.001 |
| a_{p,\mu m} | 0.2 |
| Fractal porosity (D) | 2.857 |

Other Parameters

| Parameter | Value |
|-----------|-------|
| Hanner grain-size distribution M:N | 3.4:3.4 |
| Reduced \chi^2 | 11015.16 |
| Degrees of freedom | 513 |

Notes.

* Uncertainties represent the 95% confidence level.
* Comet on 1995 October 11 UT r_h = 2.80 au, \Delta = 3.03 au.
* Number of grains, N_0, at the peak (a_p) of the Hanner grain-size distribution (GSD).
* \chi^2 = \frac{m_{cryt}}{m_{amorphous} + m_{cryst}}, where m_{cryt} is the mass fraction of submicron crystals.
* Peak grain size (radius) of the HGSD.

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Notes.

* Uncertainties represent the 95% confidence level.
* Comet on 1995 October 11 UT r_h = 2.80 au, \Delta = 3.03 au.
* Number of grains, N_0, at the peak (a_p) of the Hanner grain-size distribution (GSD).
* \chi^2 = \frac{m_{cryt}}{m_{amorphous} + m_{cryst}}, where m_{cryt} is the mass fraction of submicron crystals.
* \chi^2 = \frac{m_{cryt}}{m_{amorphous} + m_{cryst}}, where m_{cryt} is the mass fraction of submicron crystals.
