Exploring the early Evolution of our Solar System using SOFIA

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Abstract

The study of cometary dust provides key information about the formation and early evolution of the solar system. Among the processes addressed by the study of this refractory materials are: its mineralogical composition, thermal history, large-scale transport of grain material, gas-phase reactions between the gas and the dust, and processing once incorporated into larger bodies. *SOFIA* can make tremendous contributions to improving our understanding of this material. It will be vastly superior to ground-based facilities for studying the wavelengths where the best grain diagnostics are to be found - longward of 18 μm, has a better point spread function than the *Spitzer Space Telescope* at these same wavelengths, and its available solar elongation zone is less-constrained than *Spitzer* was or James *Webb Space Telescope* will be. *SOFIA* will provide the data on *solar system objects* that will be necessary for forging comparisons between the grain characteristics of these objects and those of *extrasolar disk systems* that will be observed with *JWST*. These comparisons are required in order to place the early evolution of our solar system and that of other planetary systems on a common footing.

Scientific Objectives

Understanding the origin and evolution of the solar system is one of the main goals within NASA's Strategic Plan (Sub-goal 3C, NASA Strategic Plan 2006). Observations of cometary dust provide one of the few direct links to the physical and chemical conditions of the early solar nebula. The particle size and mineralogical makeup of these grains record the nature of the refractory material from which the terrestrial planets and the cores of the Jovian planets were formed. Understanding the chemical and physical history of grain material preserved from the early solar nebula will tell us about the formation and early evolution of our solar system. Specifically:

- Is the chemical processing (fractionation, etc.) of the early solar system preserved in the grain material observable today? What does it tell us about the nature of this processing in different regions of the solar nebula?

- Is the thermal processing (thermal annealing, in situ condensation of refractories) of the early solar system preserved in the grain material preserved today? What does it tell us about the nature of this processing in different regions of the solar nebula?

While the most detailed information on comet grains comes from *in situ* sampling, the bulk of what we know about cometary grains, their origin in specific objects, and how these are related to location of formation within the early solar nebula comes from the analysis of spectral observations using ground-based, space-based, and high-altitude telescopes.

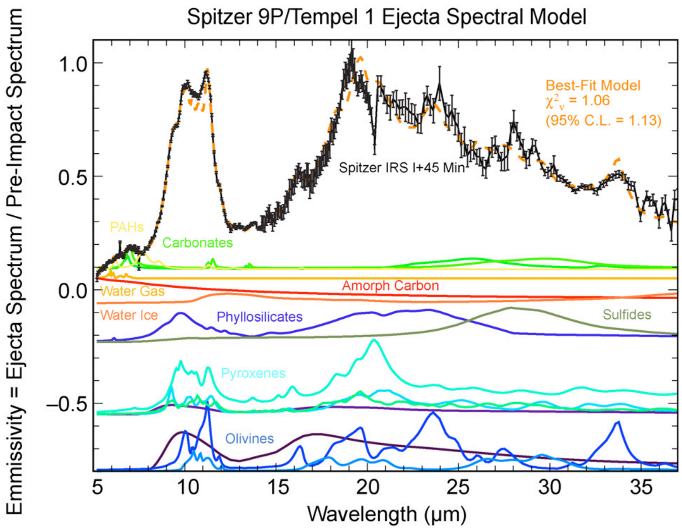
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Figure 1 – The spectrum of the material ejected from Comet Tempe 1 during Deep Impact. The best fit was obtained using a mixture of glassy (smooth curves) and crystalline (peaked curves) of pyroxene and olivine silicates, with measurable contributions from other species, most likely sulfides and possibly carbonates (from Lisse et al. 2007).

The bulk of existing mid-IR comet spectra have been obtained using ground-based telescopes, and are limited to sampling only 8-12 μm silicate band, which does not contain the diagnostic bands of most of the relevant mineral species, and where the silicate bands are highly blended, making precise mineralogical analysis difficult. The 16-45 μm region is superior in this regard, but its study was only possible using airborne facilities, such as the Kuiper *Airborne Observatory* (*KAO*) measurements of Comet Halley (Herter et al. 1987, Bregman et al. 1987, Glaccum et al. 1987), or spacecraft such as the *Infrared Space Observatory* (*ISO*) data on Comet Hale-Bopp (Crovisier et al. 1997). The launch of the *Spitzer Space Telescope* has provided us with spectra of sufficient quality (signal/noise > 50) for modeling the mid-IR spectra of about a dozen comets. Figure 1 shows an example of how an infrared spectrum of high quality can be analyzed with the aid of spectra of laboratory samples or relevant minerals. Here, the material ejected from the Deep Impact of Comet 9P/Tempel 1 was observed with the Infrared Spectrograph (IRS) of the *Spitzer Space Telescope*. It consists of a mixture of different mineral species, although the bulk of the spectral features are due to silicates of differing compositions and degrees of crystallinity.

In fact, almost all comets exhibit emission bands centered between 8-12 μm and 16-40 μm due to small silicate dust grains. The strength of this feature increases with the fraction of the grains smaller than these wavelengths. The spectral structure of these bands is also strongly correlated with their mineral content, with peak emission that is sensitive to relative amount of Mg and Fe - Mg/Fe. Figure 2 shows the spectral structure of olivine grains with varying values of Mg/Fe. The structure within these features is also a direct indicator of the crystallinity of the material, as sharp features can only be produced when a great degree of short and long range ordering is present.

The Mg/Fe content of the grains places strong constraints on the oxygen (or water) content in the inner hot region of the solar nebula, where condensation and other processing can produce the crystalline material. In a water vapor-poor region, evaporated interstellar grain material will preferentially condense into Mg-rich grains, while in water vapor-rich regions more Fe-rich material may condense. This may explain the compositional differences between the Mg-rich material in Comet Hale-Bopp (Wooden et al. 1999) and the greater mix of Mg and Fe in that of the Deep impact spectrum of Tempel 1 (Lisse et al. 2007) or the *Stardust* samples of Wild 2 (Zolensky et al. 2007).

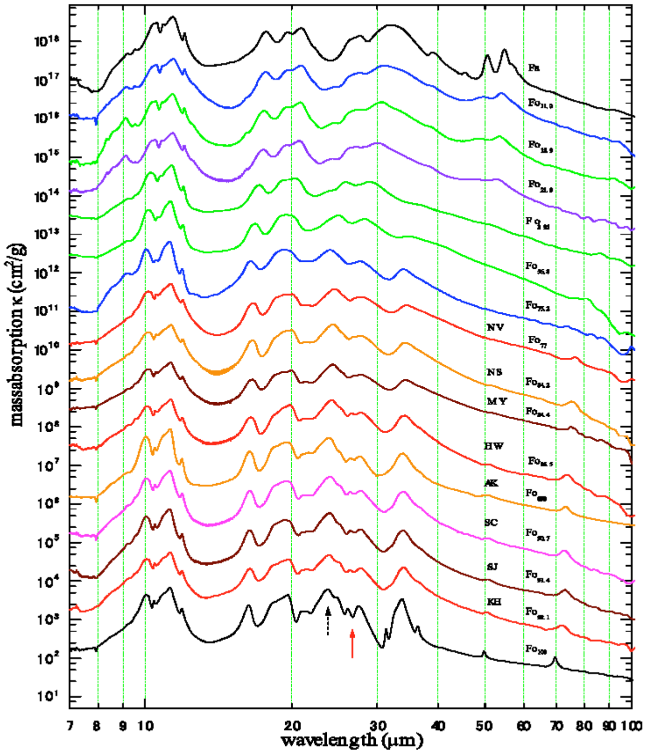


Figure 2: The spectral structure of crystalline olivine ($(Mg_xFe_{1-x})_2SiO_4$) grains as a function of Mg/Fe ratio. In this figure (and that below) the metal content is expressed as Fo_x where the pure Mg end member (x=1.0) is Forsterite. Each curve shows the spectrum with a specific value of x, decreasing from x=1.0 (pure Forsterite) at the bottom to x=0.0 at the top. Each curve has been shifted vertically and colored for clarity. Note that the scale is logarithmic, with each major labeled tic mark being a factor of 10. (Figure from Koike et al. 2003).

Despite its success at observing spectacular Oort cloud comets such as McNaught, the bulk of the highest-quality spectra of comets obtained with Spitzer are limited to the ecliptic comets – those originating in the Kuiper belt beyond the orbit of Neptune. The Oort cloud comets are believed to originate closer to the sun, and provide us with an opportunity to investigate how the nature of the material in the solar nebula changes with heliocentric distance.

For many years, evidence has accumulated that suggested that much of the primitive material in the early solar nebula was being "contaminated" by much more processed material. Despite the fact that comets formed from material that condensed beyond the "snow line" where water ice is stable against sublimation, their spectra indicated the presence of crystalline silicates. These crystalline materials comprise less than 1% of interstellar silicates (Kemper et al. 2004), so the crystalline material must either be condensed directly form gas with T > 1200 K, or me annealed close to the sun and transported radially to the comet-forming zone. Interferometric spectroscopy of other protostellar disks (van Boekel et al. 2005) show that there is a radial gradient in the abundance of crystalline silicates, much as would be expected in our own solar nebula. The Stardust sample return from Comet Wild 2 has shown that even those comets that presumably condensed from material located beyond the orbit of Neptune contain highly processed material, even Calcium Aluminum Inclusions, the highest-temperature refractory material surviving from the early solar nebula.

Our understanding of these processes will only improve with the analysis of the 16-45 μm material from a much larger sample of comets than currently exists.

SOFIA will be capable of providing the data required to answer the following questions:

- Are there compositional differences among comet families that point toward changes in chemical processing with distance in the early solar nebula?
- Are there differences in the crystallinity among comet families that are related to the radial distribution of thermally-processed material of grain material?

Using this information, it will be possible to better-characterize the physical and chemical conditions throughout the solar nebula, conditions which were responsible for determining the nature of the condensation and growth of objects from planetesimals and cometesimals to planets.

SOFIA Uniqueness/Relationship to Other Facilities

It is clear that observations of comets in the 16-45 μm region provide our most direct means of determining the nature of cometary grains. While ground-based telescopes provide the greatest degree of flexibility in scheduling, the high opacity in the 16-45 μm region makes them unsuitable for this analysis. Cryogenically cooled orbiting spacecraft, such as the *Spitzer Space Telescope*, are superior in this regard, but suffer from other deficiencies.

First, their lifetimes are limited by their supply of cryogens, which are generally not replenished. Spitzer will not last beyond 2009, for example. Once gone, the most important window for the study of the mineralogy of comet dust that we currently have is gone too.

Second, their limited supply of cryogens also usually forces strict limitations on orientation with respect to the Sun. In the case of *Spitzer*, observations closer to the Sun than 82.5° are not allowed. Most comets cannot be easily observed by *Spitzer* when they are brightest, because this occurs when they are closest to the Sun. Similarly, the restriction in the anti-solar direction is 120° solar elongation, which prevents observations when the comets are at opposition, when they are often closest to the telescope, and have the best angular resolution in km.

While there are other spacecraft capable of observations at mid-infrared wavelengths, none is better-suited to the spectroscopic study of comets than *SOFIA*.

AKARI's mission is done. Although its Infrared Camera (IRC) had spectroscopic capabilities. It offered spectral resolutions $R < 50$ out to 24 μm, and $R \sim 120$ for $\lambda = 2.5 - 5.0$ μm. The relatively low spectral resolution and short lifetime makes it unlikely that AKARI will provide the data needed for progress in cometary mineral studies.

The Wide-Field Infrared Survey Explorer (*WISE*) will have excellent sensitivity between 3 and 23 μm, but lack any spectroscopic capability.

Herschel will operate at wavelengths longward of 60 μm, where active comets will be fainter, and the mineral diagnostics more poorly known.

The James Webb Space Telescope (*JWST*) will have excellent sensitivity, and will be capable of operating out to 28 μm. The Near Infrared camera (NIRCam), Near Infrared Spectrograph (NIRSpec), and Tunable Filter Imager (TIFI) have no sensitivity longward of 5 μm and are unsuitable for cometary mineralogy. The Mid Infrared Instrument (MIRI) will provide R~100 resolution spectroscopy out to 28 μm, and is the only JWST instrument capable of adding to our knowledge in this area.

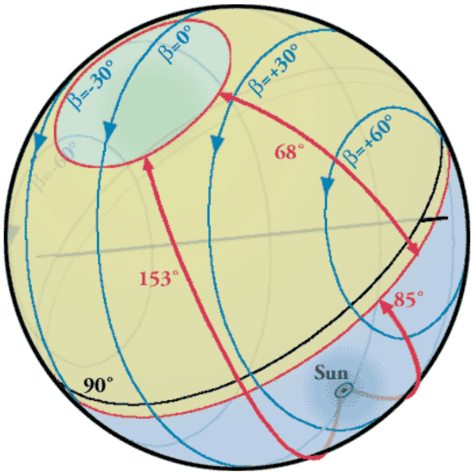


Fig. 3 - The great limitation of the JWST in the area of comet mineralogy is its limited sky coverage. Because it relies on its sun shade to operate at mid-IR wavelengths, it cannot observe any object within 85° of the Sun, nor any object within 27° of the anti-solar point.

JWST's inability to observe objects closer within 85° of the Sun means that it cannot observe comets when they are brightest, when dust production is highest, when differences in grain temperatures may be greatest (Wooden et al. 2000), and when many of the spectral features may be most easily observed. Its inability to observe objects within 27° of the anti-solar point means that it is handicapped in observing ecliptic comets when they are often closest to the earth, and provide opportunities for superior spatial resolution data/

Synergy with JWST Astrophysics

Despite the pointing limitations of *JWST*, it will be a superb instrument for investigating the mineralogy of dust in extrasolar environments, because most targets will be accessible at least twice a year, and their observation are not restricted by time and orbital constraints in the way that comets are. But one of the main goals of planetary science is to place the evolution of our own solar system within the context of that of planetary system evolution in general. This will be done by comparing the properties of solar system dust with those in these other systems. This is a task currently being done using the *ISO* and *Spitzer* observations of comets and stellar disk systems, as shown in Figures 4, 5, and 6.

SOFIA will provide the data needed to characterize the properties of the grain material in the early solar nebula, with which the dust in extrasolar disks systems, observed by JWST, will be compared.

Fig. 4 – IR spectra of the debris disk of HD 100546, compared to that of Comet Hale-Bopp, and Comet Tempel 1 prior to the Deep Impact even, as well as the DI ejecta alone. From Lisse et al. (2007)

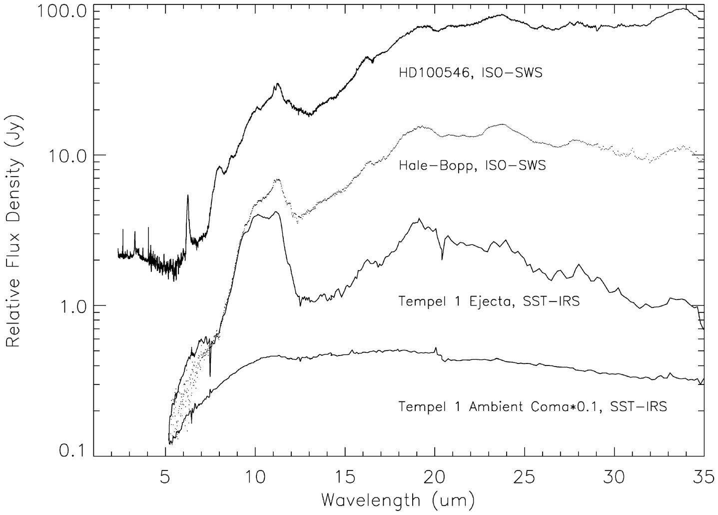


Fig. 5 – ISO spectrum Comet Hale-Bopp, along with a grain model similar to that of the material ejected from Tempel 1 during the Deep Impact event shown in Fig. 1. From Lisse et al. (2007)

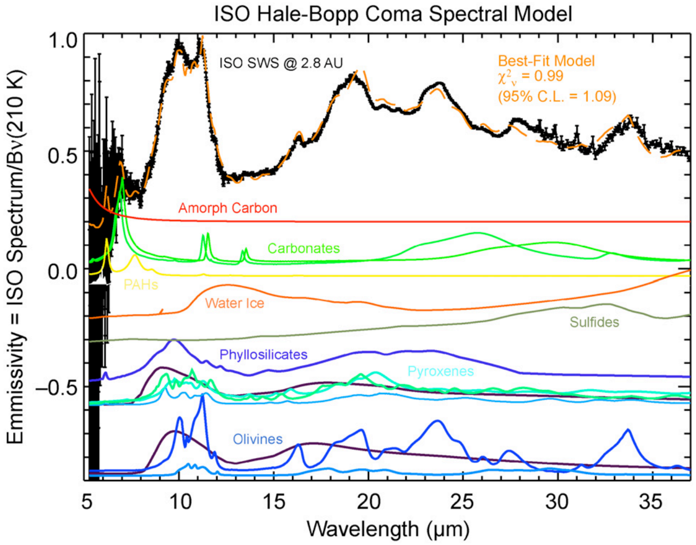
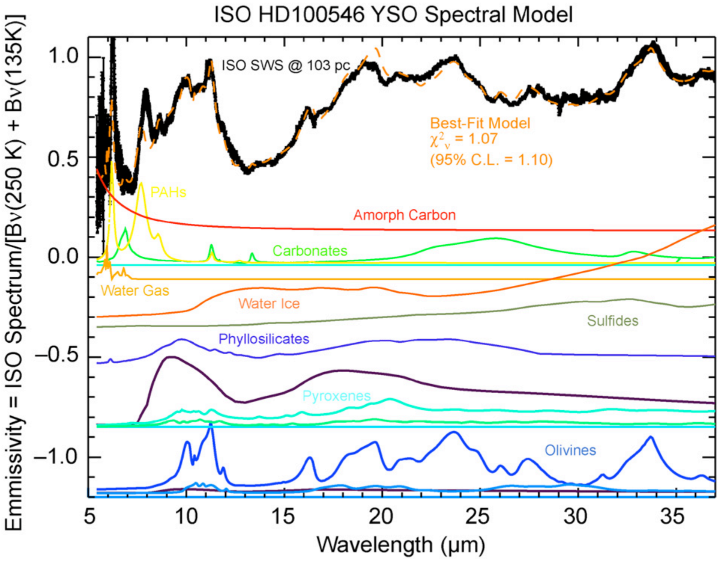


Fig. 6 – Spitzer spectrum of the dust debris disk of HD 100546, along with a grain model similar to that Hale-Bopp. From Lisse et al. (2007)



SOFIA

SOFIA has superior spatial resolution than Spitzer had, is not limited by a lifetime controlled by a single supply of cryogenics, and is considerably less restricted in its pointing with respect to the Sun than *JWST*. In particular, because we have little choice where many comets, particularly Oort cloud comets, will be in the sky, SOFIA will offer much more capable of insuring the necessary observations are possible.

One of its first-generation instruments, FORCAST, will be capable of 5-40 μm slit spectroscopy using a set of three R~200 grisms (T. Herter, private communication). For example, in 2010, comets Hartley 2 and Wild 2 will be favorably placed for observation. Wild 2 is a top-priority target because no adequate mid-IR spectrum exists for direct comparison to *Stardust* samples. The exposure times for the 17.1-28.1 μm grating and SNR=50 for Hartley 2 (V~5 mag) is less than 1 min. For Wild 2 (V~9 mag) this can be achieved in 45 min.

In summary, SOFIA will build upon the work done by the KAO, ISO and Spitzer, and while complementary to the JWST in some respects, it has, overall, much greater capabilities than JWST for providing the type of mid-IR cometary spectroscopy that is needed to answer many questions regarding the origin and evolution of the solar system.

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