SOFIA INFRARED SPECTROPHOTOMETRY OF COMET C/2012 K1 (PAN-STARRS)

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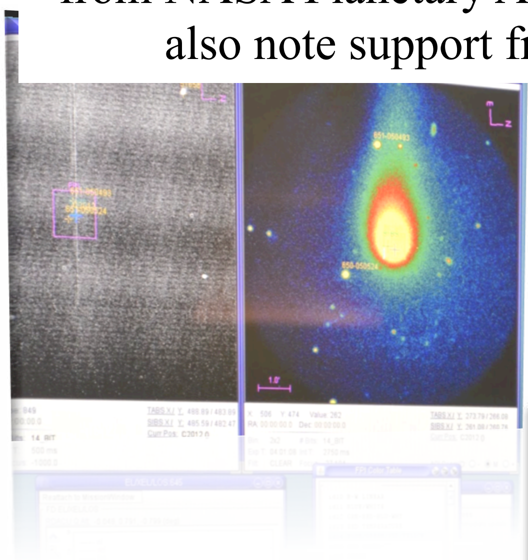


SOFIA Tele-Talk 2015.Oct.28

Scientific Context – Outstanding Questions

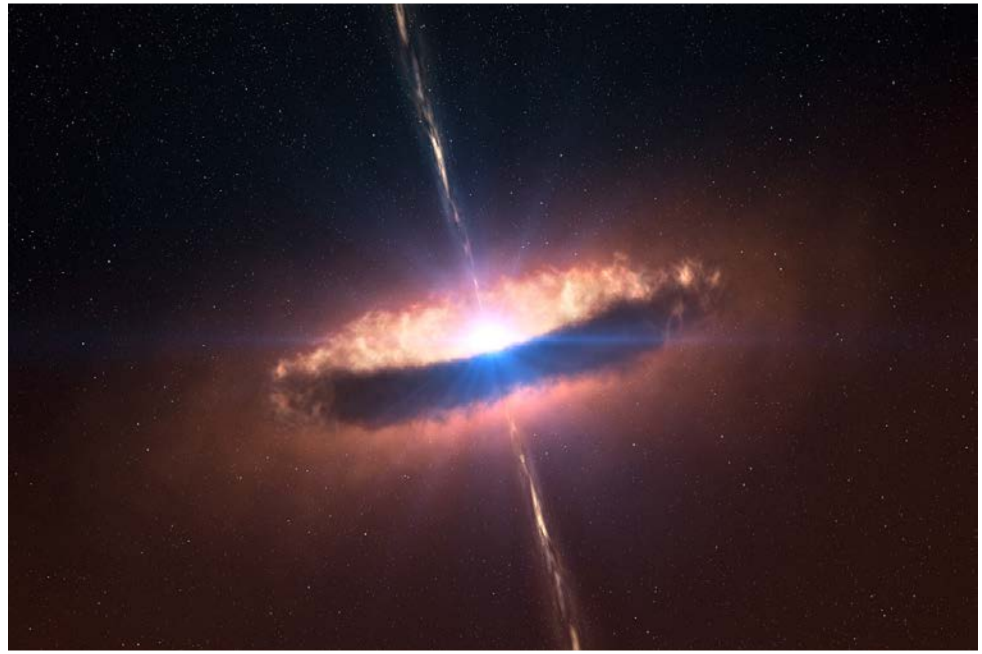
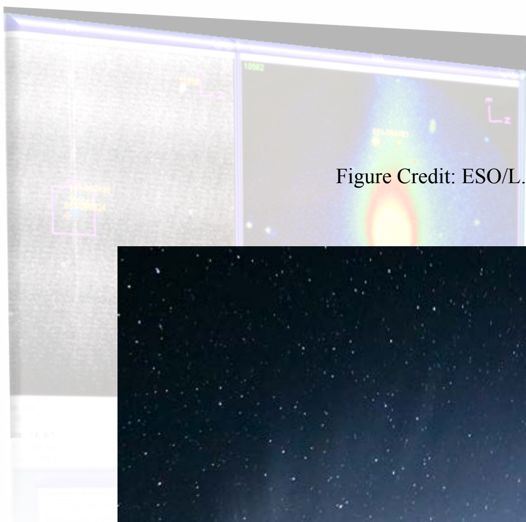


Figure Credit: ESO/L. Calcada/M. Kornmeesrt



Comet C/2006 P1 (McNaught) over the Pacific from Paranal Observatory Figure Credit: S. Deiries/ESO

Scientific Context – Outstanding Questions

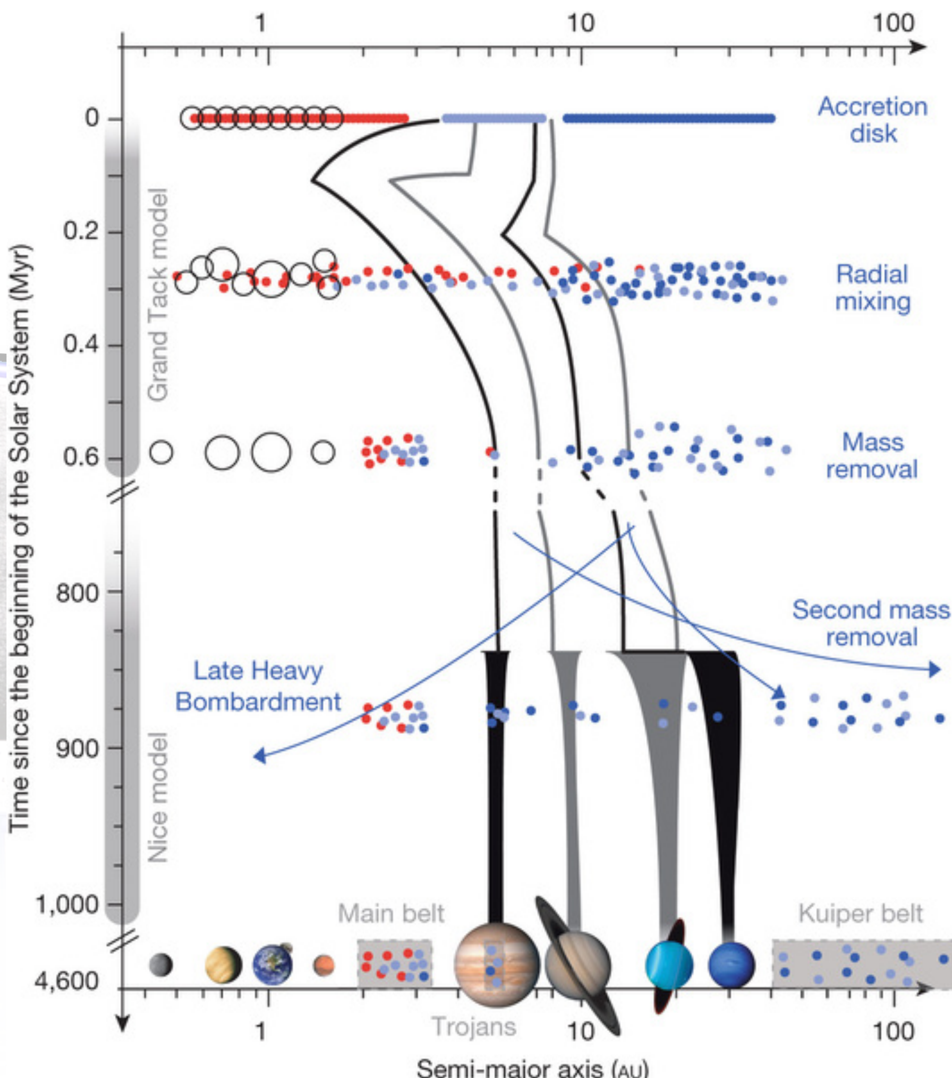


Figure Credit: DeMeo & Carry 2014 Nature, 505, 629

The properties of small, primitive bodies in the solar system, including individual comets and comet-families, whose origins lie beyond the water frost line (> 5 AU) provide critical insight into the formation of solar system solids and establishes observational constraints for planetary system formation invoking migration.

Scientific Context – Outstanding Questions

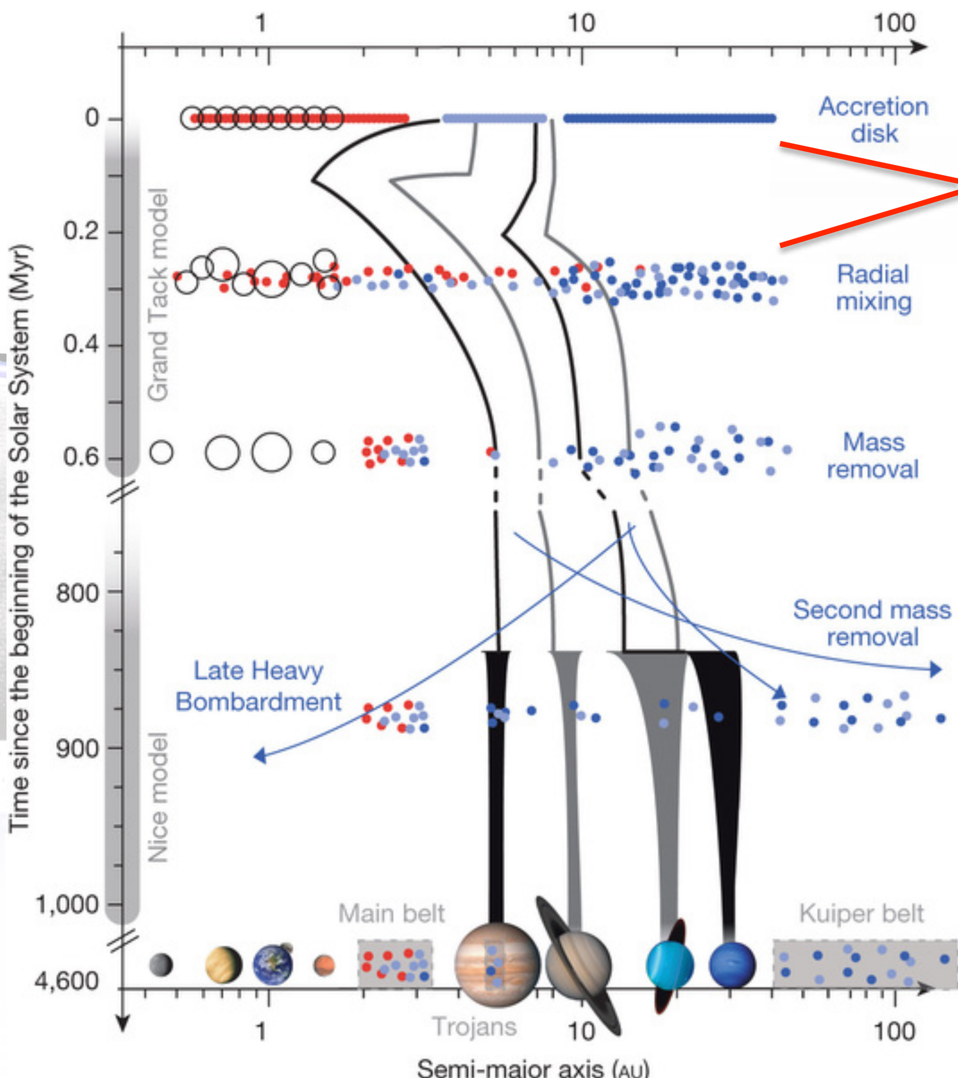


Figure Credit: DeMeo & Carry 2014 Nature, 505, 629

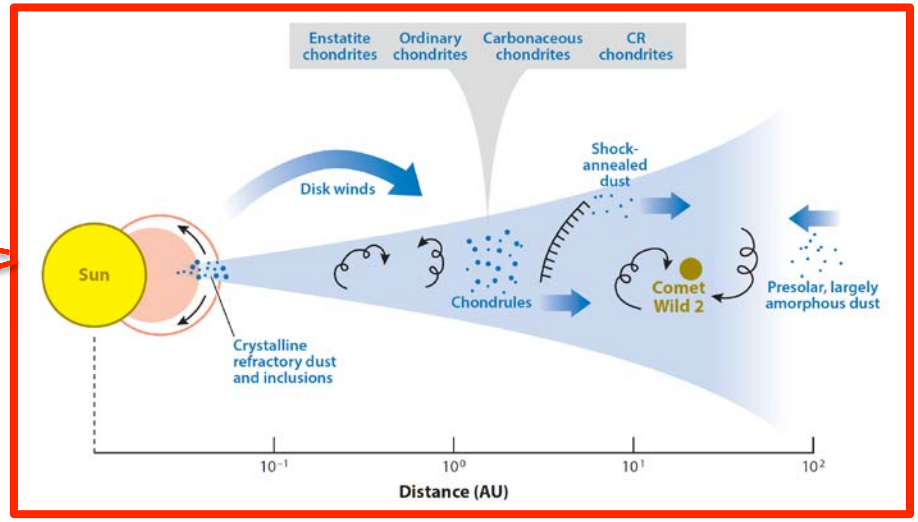


Figure Credit: Brownlee 2014, Ann. Rev. Earth Plan. Sci 42, 179

The properties of small, primitive bodies in the solar system, including individual comets and comet-families, whose origins lie beyond the water frost line (> 5 AU) provide critical insight into the formation of solar system solids and establishes observational constraints for planetary system formation invoking migration.

Scientific Context – Outstanding Questions

Perihelion distance vs. semi-major axis in a simulation of the formation of the Oort cloud. Colored markers are an initial distribution of comets that formed in the Jupiter, Saturn, Uranus, Neptune, and Kuiper Belt region (magenta blue, green, red, black). Many of the Jupiter-Saturn region comets a are quickly removed from the simulation, leaving an Oort cloud and Scattered Disk dominated by the Uranus-Neptune region comets.

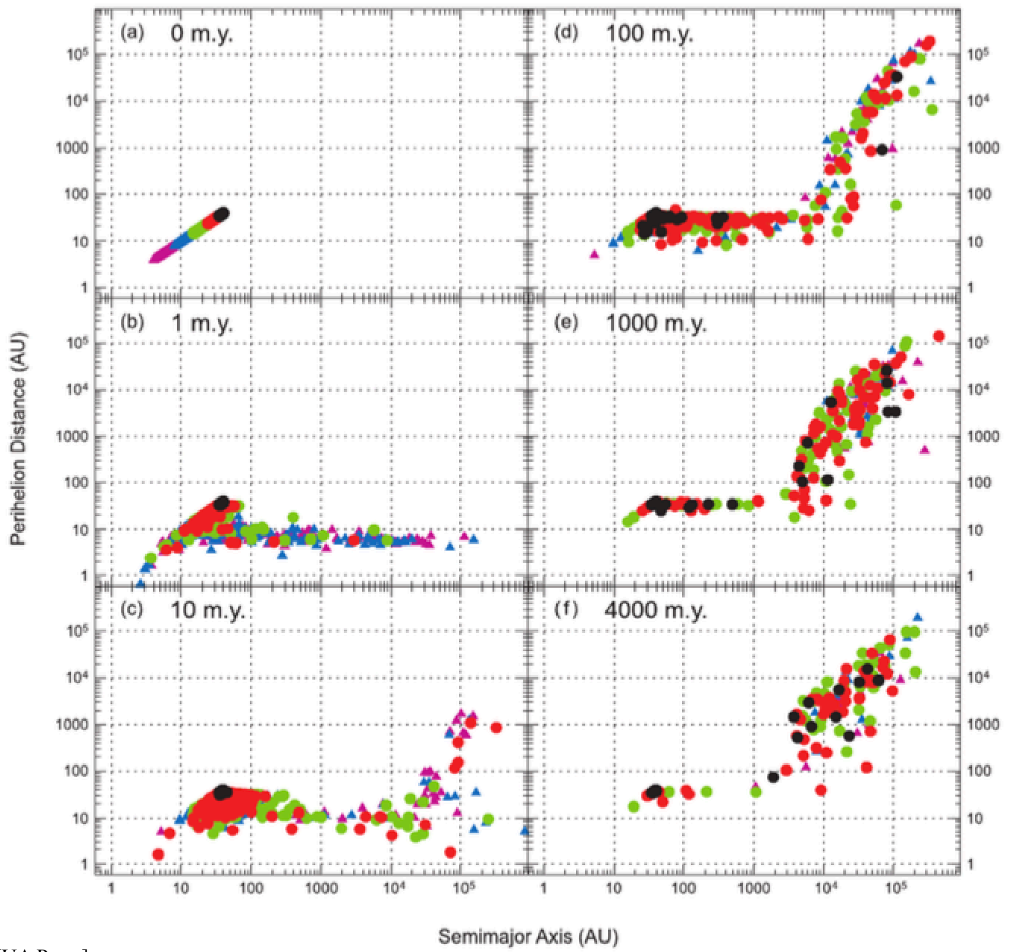


Figure Credit: Dones et al 2004, Comets II [UA Press]

Scientific Context – Outstanding Questions

Q1.
What information do cometary grains provide us concerning the evolution of the early solar system?

Q2.
What are the fundamental differences between comets originating from different regions and epochs during solar system formation?

A1.
Determine the composition of coma materials. The refractory dust in comets is much more robust in maintaining the chemical signatures from the time of formation than the more volatile ices.

A2.
Examine the differences between grain properties observed in Jupiter-family comets (JFCs) and Oort-cloud comets (OCCs). If these populations had somewhat different (but perhaps overlapping) zones of origin, we would expect to be able to detect differences in their grain properties.

The Nature of the Refractory Comet Grains

Characterization

Information derived from a variety of sources, including remote sensing through telescopic observations, in situ studies (*Rosetta*), collection of interplanetary dust particles (IDPs) in the Earth's stratosphere, and sample return (*Stardust*).

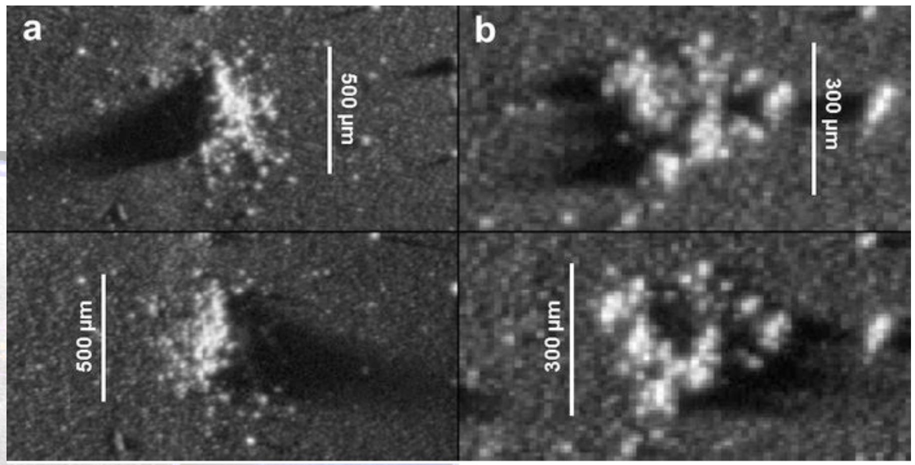


Figure Credit: COSIMA /ESA/ROSETTA

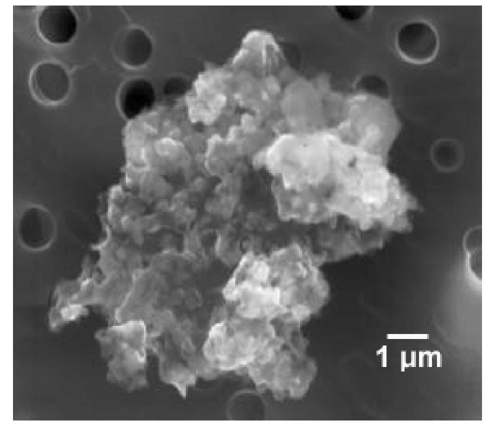


Figure Credit: NASA Johnson Space Ctr.

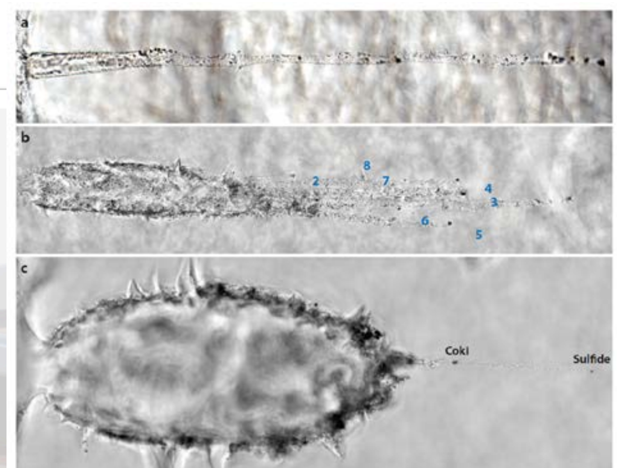


Figure Credit: Brownlee 2014, Ann. Rev. Earth Plan. Sci 42, 179

The Nature of the Refractory Comet Grains

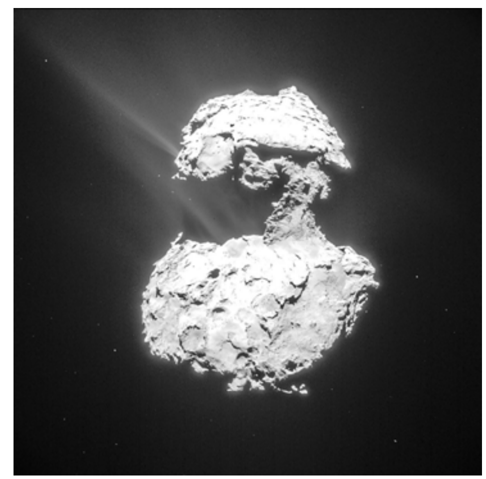
Characterization
Laboratory analysis:

Only materials from JFCs 81P/Wild 2 and 26P/Grigg-Skjellerup, the specific cometary sources of the analyzed grains remain unknown, and the IDPs materials from these known sources are vastly different.

The former comet contains material processed at high temperature, while the latter is very "primitive."

67P is also a JFC

Spacecraft encounters are very rare (all short period JFC comets).



Gases and dust rise from 67P's surface as the comet is nearing its perihelion. Figure Credit: ESA/Rosetta/NAVCAM

Statistics
Necessary to determine the properties of dust grains from a large sample of comets using remote techniques, especially those exceptional apparitions (e.g., near-Earth encounters).

SOFIA (+FORCAST) Advantage

Spectral Energy Distribution from 4.9 to 37.1 µm micron
Few high SNR spectra exist of OCCs at 4.9-8.0 µm and 28.7-37.1 µm

5-8 µm contains potential spectral signatures providing new clues as to whether organics, including carbonates and phyllosilicates are present in comets

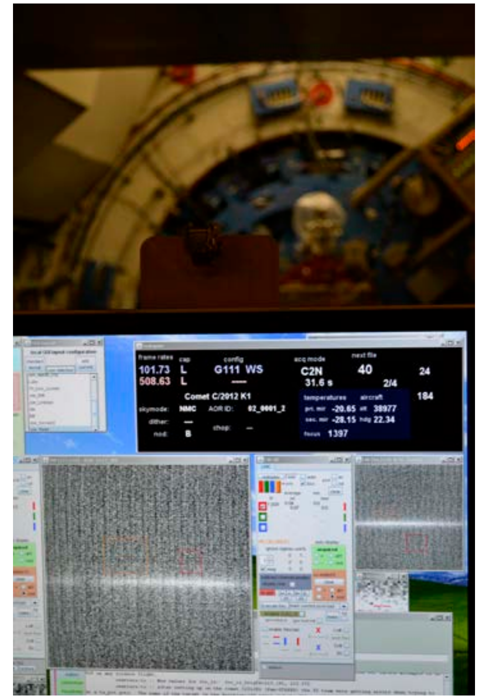
9-12µm contains features from amorphous and crystalline silicates (e.g., 11.2 µm)

17.6-37.1 µm spans the wavelength regime wherein lies broad features from amorphous pyroxene (18 µm) and Fe-Ni-S materials, and discrete resonances from crystalline silicates

Crystalline Silicates
Crystalline silicates are rare in the ISM – accounting for < 2.2% of the total silicate component in the direction of the Galactic Center and < 5% along other lines-of-site

Crystals silicates require T > 100 K to form, thus are from the inner disk and likely were transported out to the comet-forming regime and mixed with "amorphous" silicates (non-stoichiometric compositions that include the ranges of olivine [$(Mg,Fe)_2 SiO_4$] and pyroxene [$(Mg, Fe) SiO_3$])

Science Target – C/2012 K1 (Pan-Starrs)



Target:

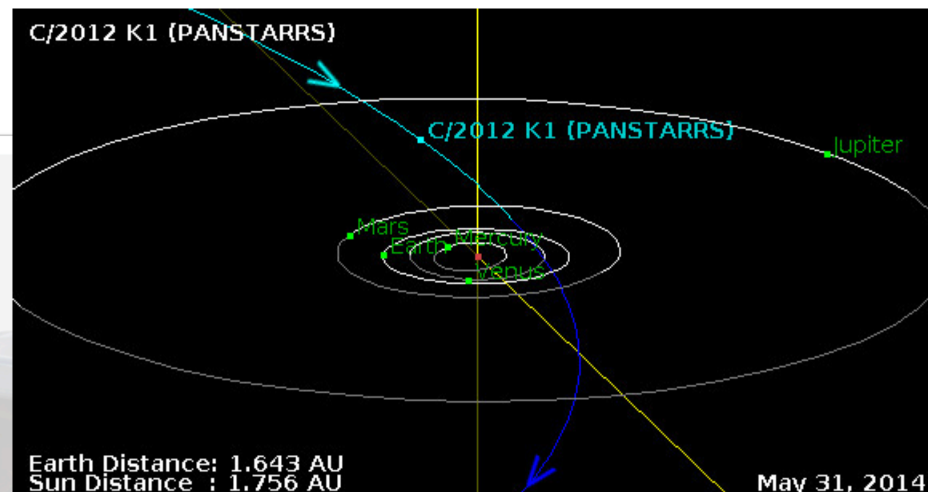
Dynamically new ($1/a_{orig} < 50e\text{-}6$) Oort Cloud comet (hyperbolic)
Perihelion date 2014-August-27.65 UT
Perihelion distance 1.055 AU

Observations:

Spectroscopy – G111, G227 Imaging – FOR_11.1, FOR_19.7
FORCAST on 4 Flights Spanning 04 through 13 June 2014

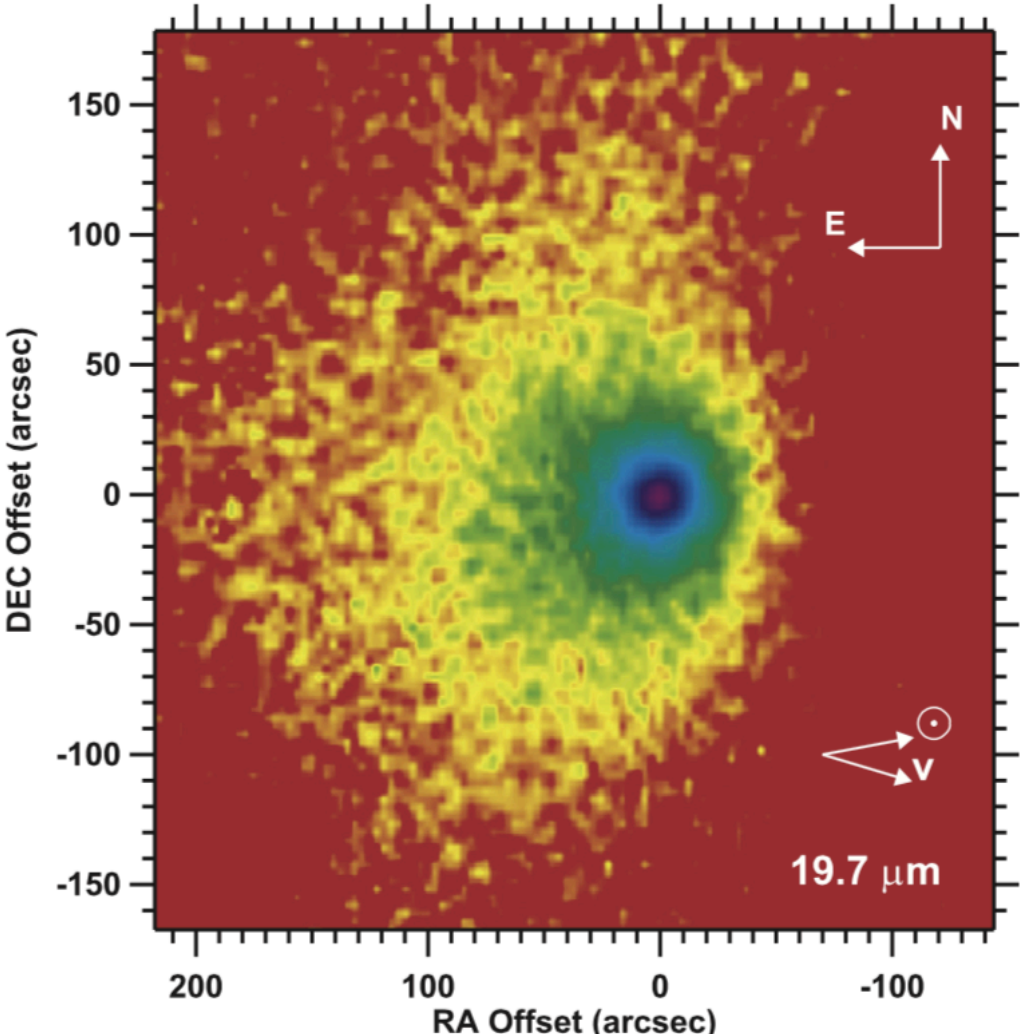
Geometry:

Average Heliocentric Distance 1.64 AU
Average Geocentric Distance 1.76 AU
Average Phase Angle 34.5°
$1/a_{orig} = 42.9e\text{-}6\ AU^{-1}$ (MPC)



Science Results – Imaging

SOFIA 19.7 μm image of comet C/2012 K1 (Pan-STARRS) obtained on 2014 June 13.17 UT, with a logarithmic color map. The vector indicating the direction of the comet's motion and the vector indicating the direction toward the Sun are also provided.



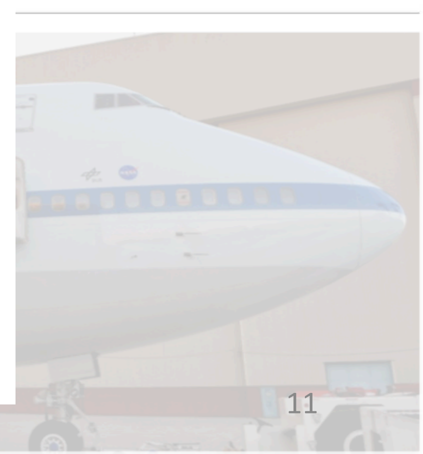
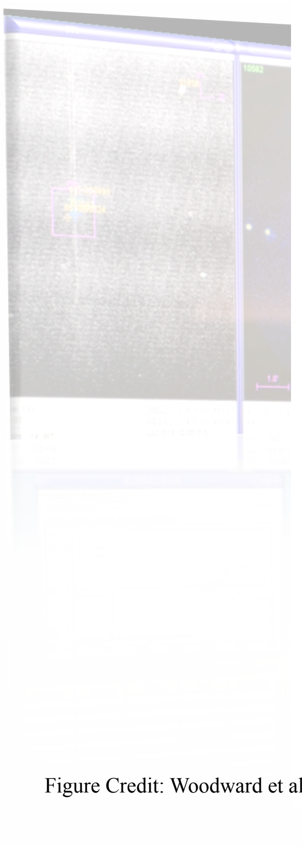
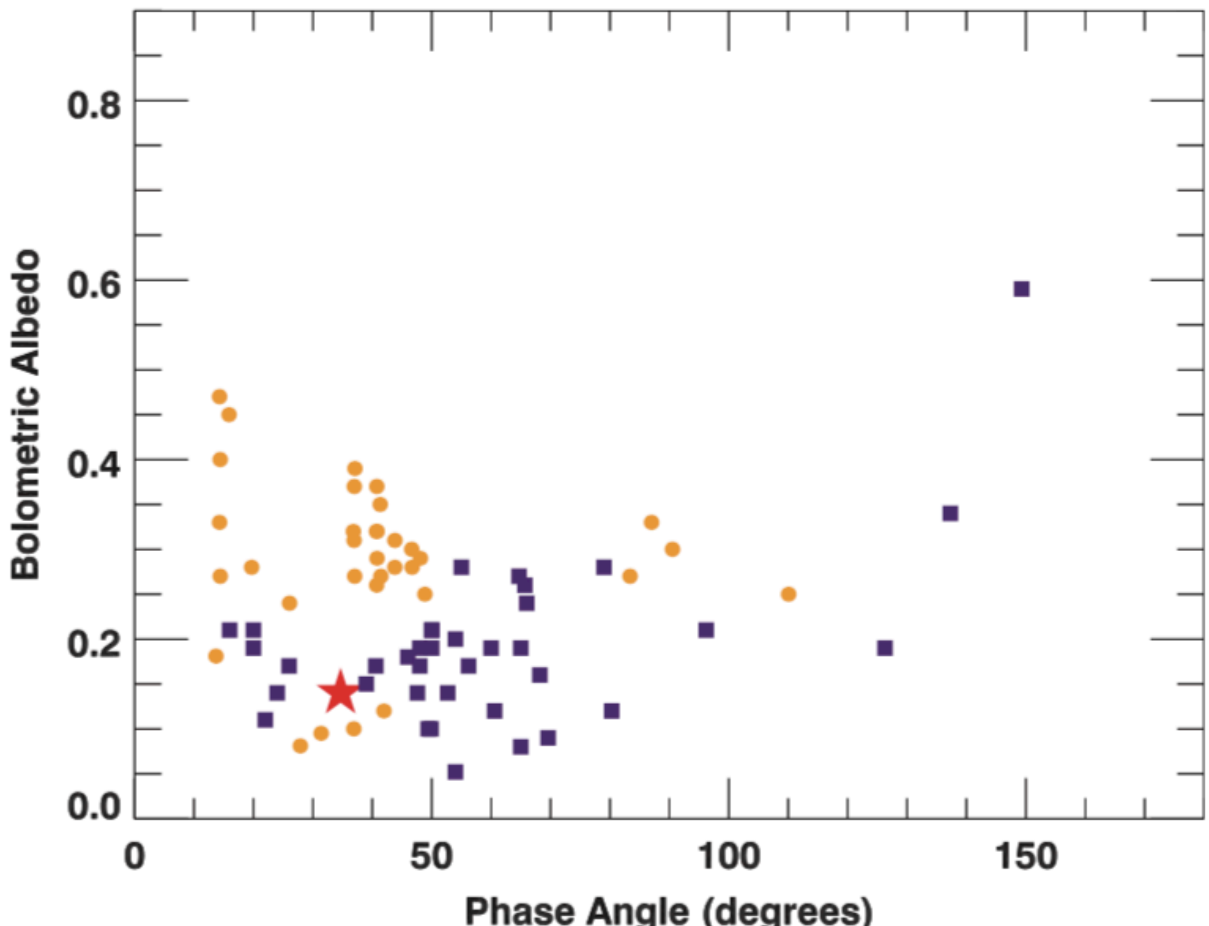


Figure Credit: Woodward et al. 2015, ApJ 809, 181

Science Results – Comet Albedo

Bolometric albedo as a function of phase angle for a sample of nearly isotropic comets (NICs; filled orange circles) and ecliptic comets (ECs; filled purple squares) derived from the literature following the prescription of Gehrz & Ney (1992). Our measurement of the NIC C/2012 K1 (Pan-STARRS), 0.14 ± 0.01 at a phase angle of 34.76°, is indicated by the red star. The phase angles for each comet are obtained from the JPL Horizons ephemerides.





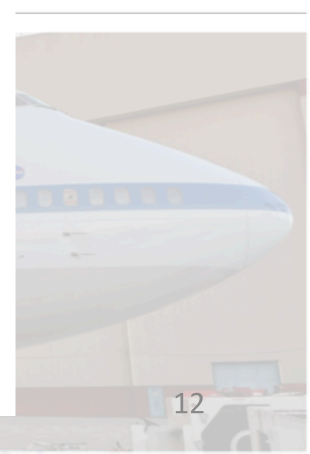


Figure Credit: Woodward et al. 2015, ApJ 809, 181

Remote Sensing – Thermal Modeling

Spectral Energy Distribution
Comet SEDs are a combination of reflected sunlight and thermal emission from dust

Shape of the thermal emission is sensitive to the dust size, structure, and composition

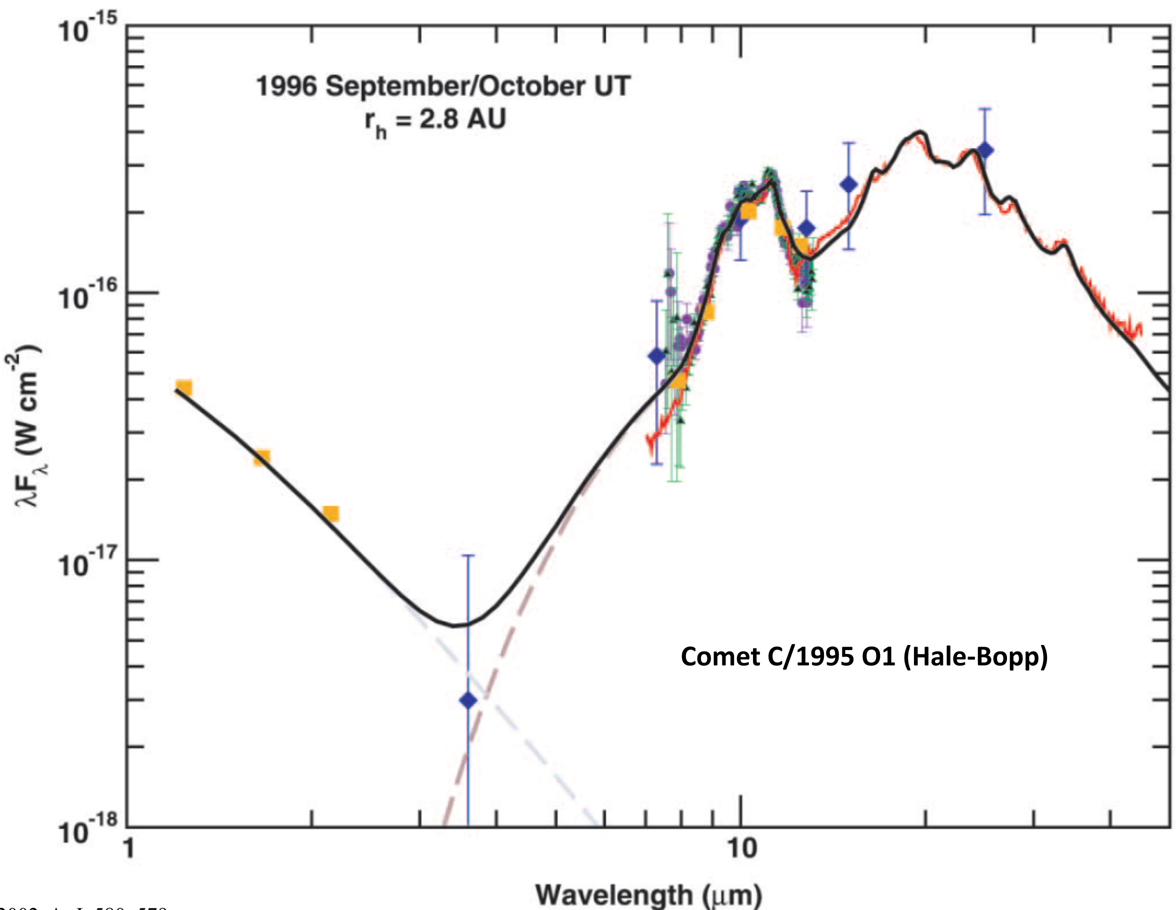


Figure Credit: Harker et al. 2002, ApJ, 580, 579

Remote Sensing – Thermal Modeling

Model Details
Gains in come optically thin environment

Uses four minerals: amorphous olivine and amorphous pyroxene with broad 10 and 20 μm emission features, amorphous carbon with featureless emission, and crystalline olivine with narrow peaks

Amorphous carbon component in our dust model is representative of possibly several key dust species – elemental carbon dust, an organic component with C=C bonds, that can include amorphous carbon, and possibly other carbonaceous grains

No Fe-Ni-S materials (optical constants are not readily available).

Broad and narrow resonances near 10 and 20 μm are modeled by warm chondritic (50% Fe; 50% Mg) amorphous silicates (i.e., glasses) and strong 11.25, 19.5, and 24 μm narrow features from cooler Mg-rich crystalline silicate materials

Model Outputs
Chi-squared constraints on temperatures, size distributions (n(a)da), porosity, and relative mineral abundances

Science Results – The Spectral Energy Distribution

Spectral decomposition of the grism observations of comet C/2012 K1 (Pan-STARRS) derived from thermal modeling. Filled circles are the broadband photometric observations obtained on 2015 June 04 UT when each of the filters were observed on a single flight.

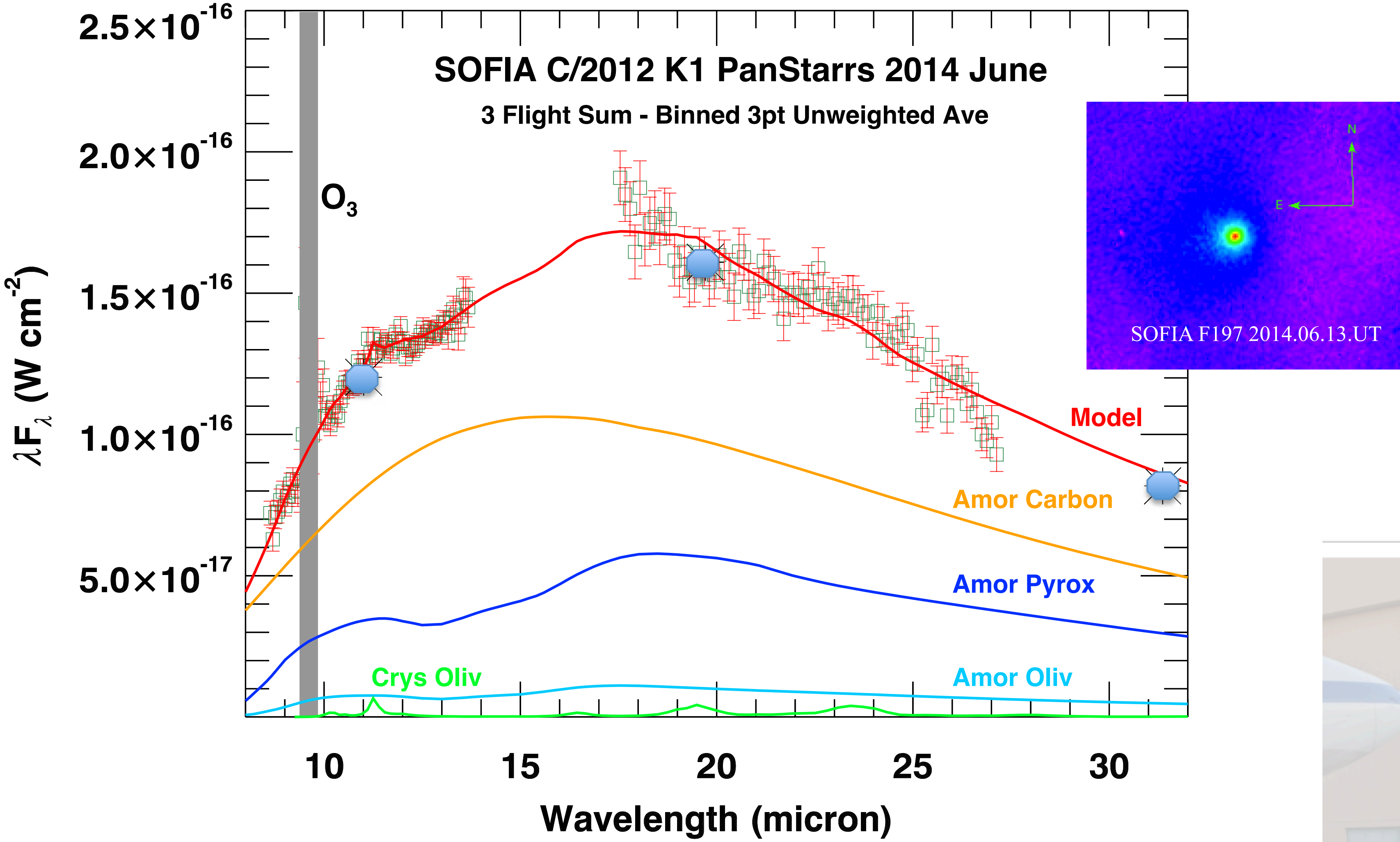
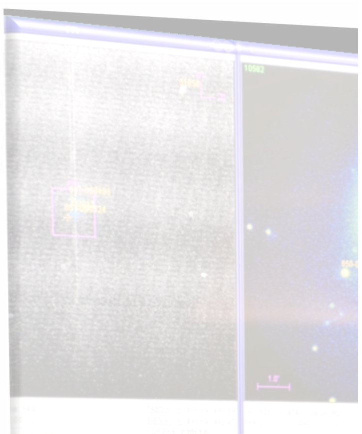


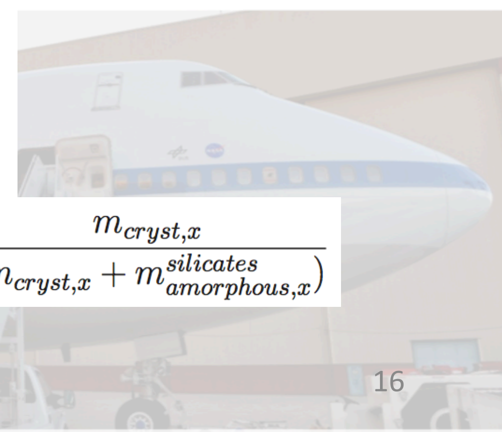
Figure Credit: Woodward et al. 2015, ApJ 809, 181

Science Results – Thermal Models and Grain Composition

Dust component	N_p[a] $\times 10^{16}$	Sub-μm mass fraction
Amorphous pyroxene	$8526.433^{+1067.813}_{-1494.938}$	$0.310^{+0.043}_{-0.060}$
Amorphous olivine	$1228.326^{+213.563}_{-640.688}$	$0.045^{+0.009}_{-0.026}$
Amorphous carbon	$15246.560^{+213.563}_{-427.125}$	$0.555^{+0.009}_{-0.017}$
Crystalline olivine	$2476.880^{+2135.626}_{-854.250}$	$0.090^{+0.078}_{-0.031}$
Crystalline pyroxene	$0.000^{+1067.813}_{-0.000}$	$0.000^{+0.043}_{-0.000}$
Other model parameters		
χ^2_ν	0.98	
Degrees of freedom	156	
Total submicron grain mass[b]	$(7.663^{+1.310}_{-0.952}) \times 10^5$ kg	
Silicate/carbon ratio	$0.80^{+0.25}_{-0.20}$	
f_{cryst}	$0.202^{+0.297}_{-0.099}$	

$$f^{silicates}_{cryst} \equiv \sum_{x=1}^{n} \frac{m_{cryst,x}}{(m_{cryst,x} + m^{silicates}_{amorphous,x})}$$





Thermal Modeling of SOFIA SED C/2013 K1 (Pan-STARRS) -- Adopted from Woodward et al. 2015, ApJ 809, 181

Science Results – Thermal Models and Grain Composition

Highlights
Mineralogically, the grains in the coma of C/2012 K1 (Pan-STARRS) are dominated by amorphous materials, especially carbon

HGSD differential grain size distribution peaks (modified power-law) with grains of radii 0.6 μm, indicating relatively moderately larger grains are present

Grains in the coma of C/2012 K1 (Pan-STARRS) also are solid (the fractal porosity parameter D = 3.0)

10μm silicate feature in comet C/2012 K1 (Pan- STARRS) is quite weak compared to comets like C/1995 O1 (Hale-Bopp) or 17P/Holmes

Comparative Aspects
Bulk grain properties of comet C/2012 K1 (Pan-STARRS) are comparable to other NICs with weak 10μm silicate features and

Bulk grain properties similar in respect to coma grains seen in the small set of ECs that have fragmented, explosively released subsurface materials, or have had materials excavated from depth.

Science Results – Comet Crystalline Mass Fractions

$$f_{cryst}^{silicates} \equiv \sum_{x=1}^{n} \frac{m_{cryst,x}}{(m_{cryst,x} + m_{amorphous,x}^{silicates})}$$

Silicate Crystalline Mass Fraction

To the first order, the diversity of comet dust properties reflects the temporal and radial gradients in our solar system's early history

Similarities and differences in dust characteristics, including f_{cryst}, may provide observational tests of of planetary migration models within the early solar system during the epoch of planet formation that resulted in a variety of small body dynamical populations.

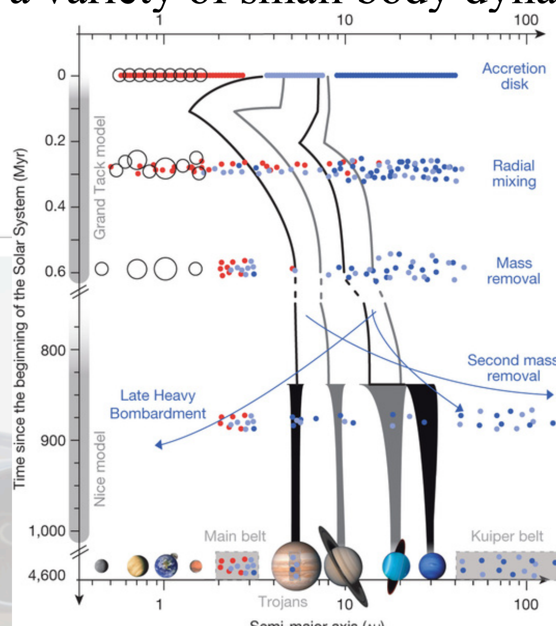


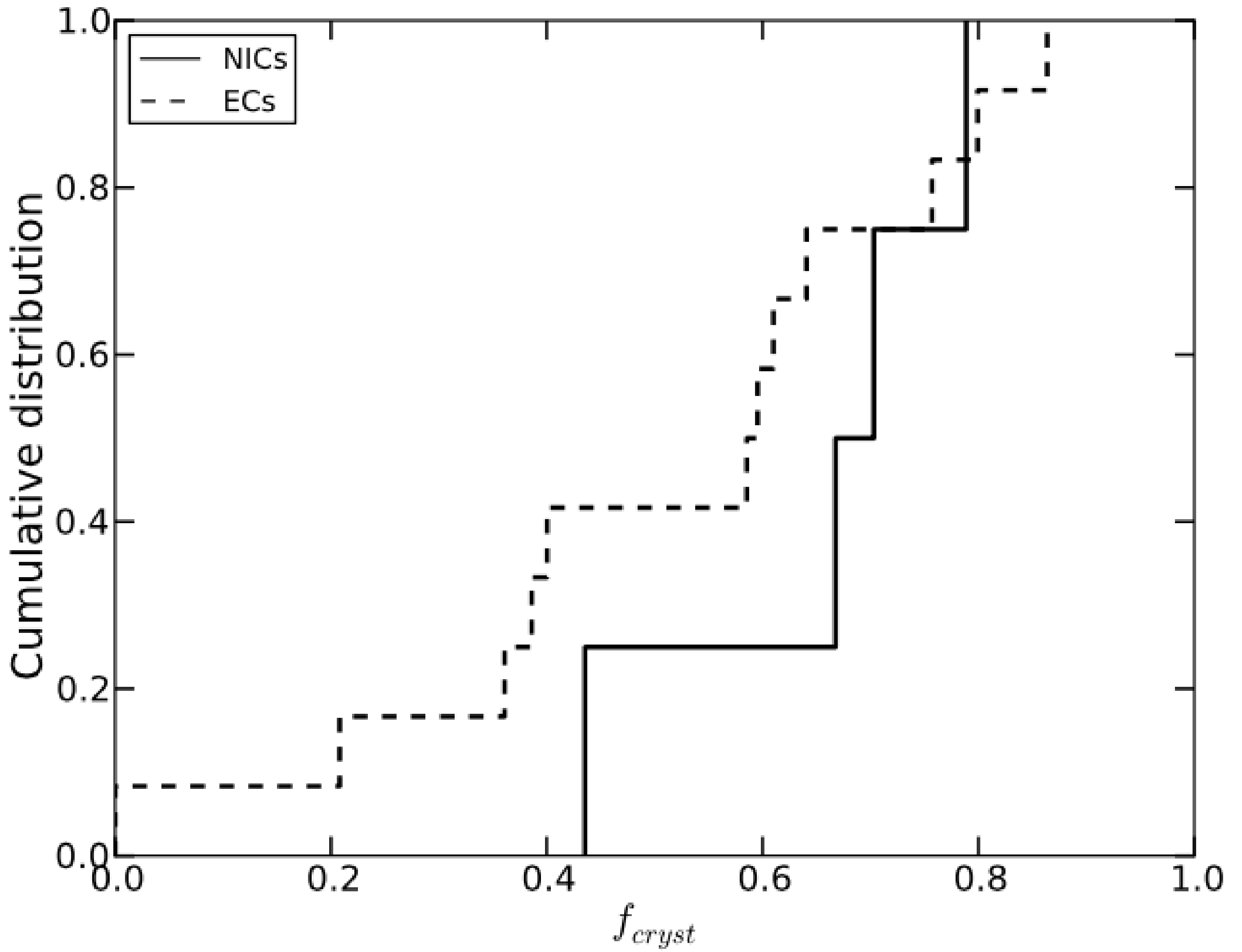
Figure Credit: DeMeo & Carry 2014 Nature, 505, 629

Science Results – Comet Crystalline Mass Fractions

Comet Class	$1/a_{orig}$ (10^{-6} AU^{-1})	f_{cryst}[a] Range (%)	SAC[b] Ratio	N	a_{peak} (μm)
NIC/OC[c]					
C/2012 K1 (Pan-STARRS)	42.9	10-50	0.6-1.1	3.4	0.6
C/2007 N3 (Lulin)	32.2	34-51	0.42-0.54	4.2	0.9
C/2001 Q4 (NEAT)	61.2	71	1.7-5.7	3.7	0.3
C/2002 V1 (NEAT)	2279.3	66-69	1.38	3.7	0.5
C/1995 O1 (Hale-Bopp)	3805.0	60-78	8.1-13.3	3.4-3.7	0.2
EC/JFC[c]					
9P/Tempel 1 (~ 1hrs post-impact, ctr)	...	19-25	3.4-4.4	3.7	0.2
17P/Holmes	...	~ 42[c]	0.2	...	...
73P/SW3-B (Apert B)	...	43-69	1.09-1.59	3.4	0.5
73P/SW3-C (Apert M)	...	57-69	0.60-0.75	3.4	0.3

Thermal Modeling Dust Characteristics of Select Comets -- Adopted from Woodward et al. 2015, ApJ 809, 181

Science Results – Comet Crystalline Mass Fractions



Cumulative distribution function of comet silicate crystalline mass faction grouped by dynamical class -- Adopted from Kelley et al. 2015 in preparation

Future Directions with SOFIA

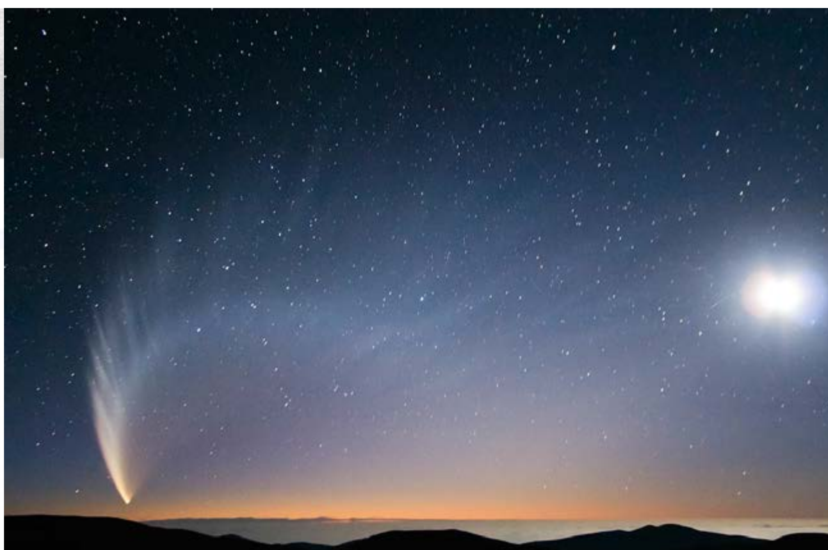
Highlights
10 Hrs of Cycle 4 SOFIA(+FORCAST) target time awarded

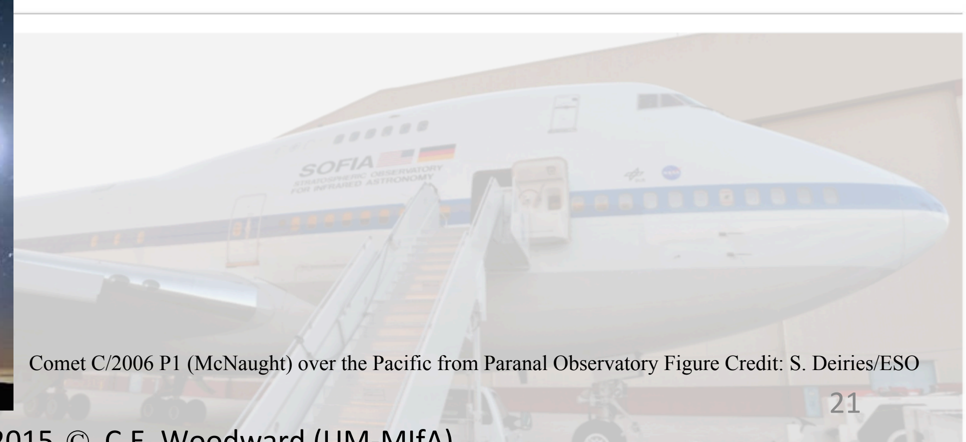
C/2012 US10 (Catalina) [Palmdale deploy]

C/2013 X1 (Pan-STARRS) [Christchurch, NZ deploy]

Driven By Grand Challenge Questions
How do circumstellar disks evolve and form planetary systems?

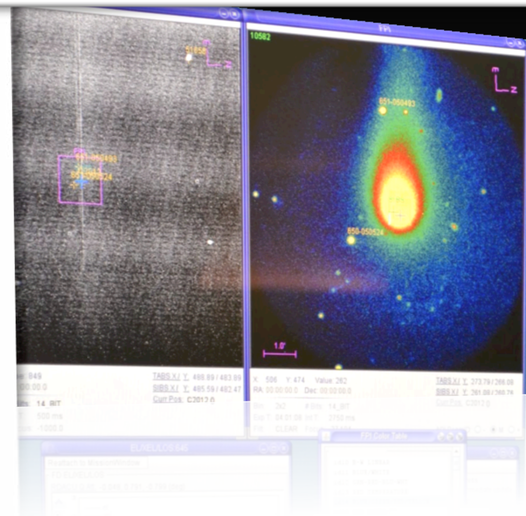
"What are the initial stages, conditions and processes of Solar system formation and the nature of the ISM that was incorporated?"





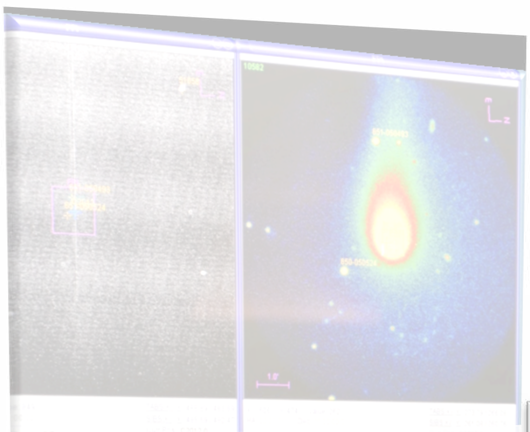
Comet C/2006 P1 (McNaught) over the Pacific from Paranal Observatory Figure Credit: S. Deiries/ESO

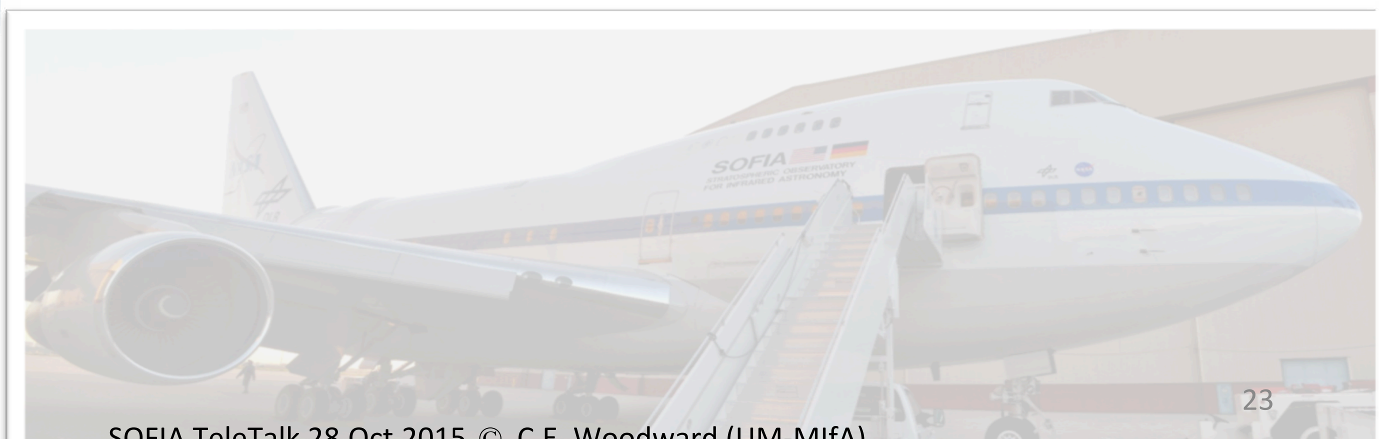
Future Directions with SOFIA



SOFIA – C/2012 K1 (Pan-STARRS)

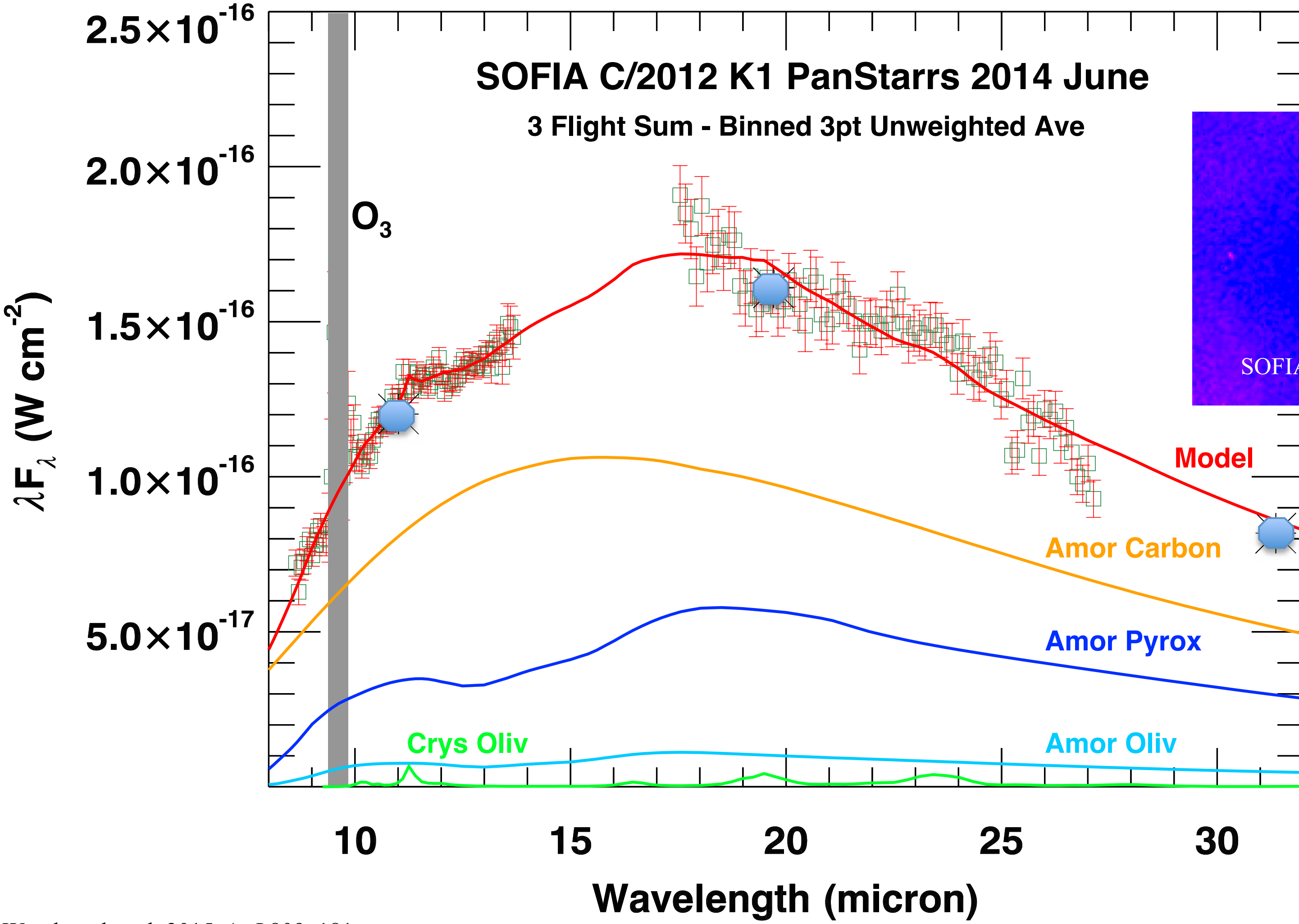
BACKUP SLIDES





Science Results – The Spectral Energy Distribution

Best-Fit Model Parameters: N = 3.4, M = 17, a_{peak} = 0.6 micron, $D_{porosity}$ = 3.0, Sil/C = 0.64
Crystalline Mass Fraction ~ 0.2



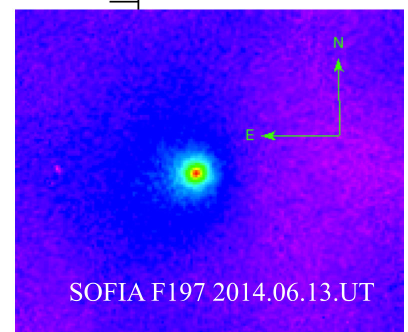


Figure Credit Woodward et al. 2015, ApJ 809, 181

SOFIA – C/2012 K1 (Pan-STARRS)

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