REFLECTANCES OF ICY SOLAR SYSTEM BODIES AT λ > 2.5 µm. J.P. Emery[1], C.M. Dalle Ore[1], D.P. Cruikshank[2], Y.R. Fernandez[3], D.E. Trilling[4], J.A. Stansberry[4] [1]Carl Sagan Center, SETI Institute (jemery@carlsagancenter.org), [2]NASA Ames Research Center, [3]Dept. of Physics, Univ. Central Florida, [4]Steward Observatory, Univ. Arizona.

Introduction: Attendees of this workshop share a common understanding that ices and organics of various compositions are important in many planetary and astrophysical environments. In our collective efforts to characterize the compositions of these materials as fully as possible, observations spanning the electromagnetic spectrum are critical. Reflectance measurements at λ > 2.5 µm are particularly sensitive to the detection of most ices and simple and complex organics. The energies of fundamental vibrations of many relevant molecular bonds (O-H, C-H, N-H, C-O, etc.) fall in this wavelength range. The resulting absorption bands are much stronger than the overtone and combination bands detected at shorter wavelengths.

Unfortunately, ground-based observations at λ > 2.5 µm are very difficult (impossible at some wavelengths) due mainly to strong absorptions in Earth's atmosphere from gases such as H_2O, CO_2, and CH_4 and increasing levels and variability of thermal background flux. As a consequence, only the brightest asteroids, icy satellites, and KBO (Pluto) are observable from the ground in this wavelength range. Although the resulting data are not always of the highest quality, they have enabled the characterization of hydrated material on asteroids [e.g., 1], the H_2O and non-ice materials on satellites of Jupiter and Saturn [e.g., 2,3,4,5] and methane and non-volatile components on the surfaces of Triton and Pluto [6,7,8]. The mapping spectrometers NIMS and VIMS on the Galileo and Cassini spacecraft have brilliantly demonstrated the benefits of observing at λ > 2.5 µm from outside Earth's atmosphere, sensing a variety of materials on jovian and saturnian satellites, including CO_2 (perhaps bound), SO_2, several organics, amorphous H_2O, and H_2O_2 [e.g., 9,10,11,12,13,14].

This handful of observations has been critical for understanding these objects, but the sample represents only a miniscule fraction of bodies that are expected or known to contain volatiles. Moving forward with prospects for much larger sample sizes from SOFIA and James Webb, it is timely to re-evaluate the promise of reflectance observations at λ > 2.5 µm. As a start, we present an overview of photometric observations of KBOs, Centaurs, icy satellites, and Trojan asteroids using the Spitzer Space Telescope. These observations use the Infrared Array Camera (IRAC), an imager with filters centered at 3.6, 4.5, 5.8, and 8.0 µm.

KBOs and Centaurs: We have enacted two programs so far to observe KBOs and Centaurs with IRAC. The first, in cycle 2 (2005-2006) measured fluxes of 12 KBOs and 8 Centaurs. The second program, from cycle 4 (2007-2008), targets 20 additional KBOs and 5 Centaurs. Most of the targets from cycle 4 have not yet been observed. Reflected fluxes from KBOs in these programs are generally detectable at 3.6 and 4.5 µm with IRAC, but are too faint at 5.8 and 8.0 µm. From cycle 2, all 12 KBOs were detected at 3.6 µm and 11 of them were also detected at 4.5 µm. All but one (1996 TL66) exhibit significant absorption at λ > 2.5 µm (e.g., Fig. 1), even many with no discernable ice absorptions at shorter wavelengths. KBOs are all so cold that thermal flux is negligible in the IRAC bands.

H_2O ice has been detected on several KBOs and Centaurs through absorptions at 1.5 and 2.0 µm. Many others do not exhibit these bands, but much of the NIR data have low S/N. Because H_2O contains very strong absorptions at λ > 2.7 µm, the 3.6 µm IRAC channel provides a sensitive test for water ice. We have found that the IRAC data points are also sensitive to the presence of other ices, such as CH_4 and CH_3OH (see Fig. 1). Aside from a likely dynamical family associated with 2003 EL61, there is no apparent correlation between the presence of vis-NIR H_2O bands and any other dynamical or physical property [15,16]. The greater sensitivity provided by observations at λ > 2.5 µm will more robustly identify such correlations if they exist.

Pluto and other dwarf planets: Being much brighter than other KBOs, Pluto was easily detected in all four IRAC bands, significantly extending the wavelength coverage of reflectance measurements. Observations were made at eight distinct longitudes, providing rotational lightcurves in all four bands. The 3.6 µm band exhibits a strong absorption that is in agreement with ground-based spectra in this region and matches the expected behavior of the CH_4 apparent at shorter wavelengths. The other three bands show higher reflectivity, and the 4.5 µm lightcurve seems to be distinct from the lightcurve at any other wavelength.

Eris, 2003 EL61, and 2005 FY9 are included in the cycle 4 program, but have not yet been observed. Depending on the strengths of absorptions, these three bodies may also be detectable in all four IRAC bands.

Icy satellites: Several satellites of the outer planets have also been observed using IRAC. These are generally also bright enough to have been detected in all four bands. For many of them, however, scattered light from the planet is a bit of a problem, making the photometric extraction somewhat more complicated than for isolated targets.

Trojan asteroids: Though no ice has been detected on their surfaces, Trojan asteroids are often assumed to support interior ice, or to have at least originated in an ice-rich part of the solar nebula. The two KBO and Centaur programs mentioned above also include observations of 10 Trojan asteroids each. The Trojans are much warmer than KBOs and most Centaurs, and thermal flux dominates the 8-μm band and is a significant contributor to the flux at 5.8 μm. The 3.6 and 4.5 μm bands, however, do provide measurements of reflectance.

Along with searches for ices, characterization of the "dark material" that provides the low albedo and red slope is important for Trojan asteroids and many Centaurs with similar vis-NIR spectra. The neutral to moderately red spectra of these objects can be explained equally well with silicates or a variety of organics [e.g., 17,18]. Silicates and organics have very different spectral behavior at $\lambda > 2.5$ μm, and observations in this wavelength range will allow us to discriminate between these two possible surface compositions.

Thermal emissivity: With another instrument, the Infrared Spectrograph (IRS), Spitzer has also measured mid-IR (5.2 – 38 μm) emissivity spectra of a slew of asteroids, including Trojans, and several Centaurs and KBOs. These measurements are far more sensitive to the silicate component than the ice component of the surfaces, so are not directly relevant to the Science of Solar System Ices workshop. However, the emissivity signatures of the Trojan asteroids and some of the Centaurs, while showing clear signs of silicate mineralogy, are very different than we expect for a regolith based on current laboratory data and radiative transfer models [19]. It is unclear whether the differences are due to mineralogy, grain size, surface structure (e.g., porosity or inclusions), mixing, or some other effects. Additional laboratory studies of emissivity of materials and conditions appropriate for these outer Solar System surfaces are necessary to properly interpret the emissivity data.

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__Figure 1.__ IRAC data for the KBO Sedna (filled and open circles) along with the vis-NIR spectrum and three spectral models. The colored Xs are the values of the models convolved with the IRAC filter functions. The presence of CH_4 reported by Barucci et al. (2005) is confirmed. Furthermore, analysis of the full wavelength range suggests the presence of H_2O. Both ices are required to fit the IRAC reflectances.