Infrared Characterization of TNOs

Spitzer, Herschel and JWST

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IAC Winter School
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TNO/Small-body Physical Properties

• After “there it is” – “what it is?”
  1. Size, shape, reflectivity, mass, density, temperature, color, …
  2. Atmosphere, thermal character, composition (surface, interior), …
  3. Geology, history, compositional heterogeneity, activity, …

• Global properties (1, 2) determined telescopically
• Surface variations (3) determined via spacecraft encounter
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• A few basic concepts and principles
• Spitzer & Herschel – Thermal method
• JWST - Compositions
Herschel

- Infrared Space Observatory (ESA): 2009 – 2013 (4 years cryogenic)
- 3.5 m telescope, L2 Orbit
- Photometry and spectroscopy (55 to 672 μm), liquid helium cooled instruments PACS, SPIRE, HIFI
- Telescope passively cooled to ~70K

“TNOs are Cool” Key Programme: photometric (PACS & SPIRE) observations of about 130 TNOs/Centaurs; PI: T. Müller
Spitzer Space Telescope

- 85-cm Beryllium mirror, T < 15 K
  - Diffraction Limit: 5.5 μm
  - Background Limited 3 – 160 μm

- Three Focal Plane Instruments
  - ~5K operating temperatures
  - Imaging: 3.6 - 160 μm
  - Spectroscopy: 5.3 – 40 μm
  - SED: 51 – 106 μm

- Heliocentric Earth Trailing Orbit

- Launched warm, cooled down on orbit
  - Cryogenic mission lasted 5.5 years
  - Warm mission (3.6 & 4.5 μm imaging) continues until ~2017.
Spitzer: Earth-Trailing Solar Orbit

- IOC/SV
- Mission Lifetime Req't
- Thru Cryo Depletion
- Warm Mission

Oct 2018
Oct 2016

30-day time ticks on trajectory

Spitzer location @ Cryo depletion on 15-May-2009

circle of radius 1 AU from Sun
A large low-albedo object can reflect the same amount of sunlight as a small high-albedo object…

However, large low-albedo objects emit much more in the thermal (larger and warmer)…
Thermal Method Basic Equations

\[ T_{SS} = \left( \frac{S_0(1-A)}{\eta \varepsilon \sigma} \right)^{1/4} \]

- \( S_0 \) = Insolation (W/m²)
- \( A \) = Bolometric Albedo
- \( \eta \) = “Beaming Parameter”
- \( \varepsilon \) = emissivity
- \( \sigma \) = Stefan-Boltzmann constant

\[ A = q \ p_V \]

- \( q \) = phase integral

\[ H_V = V - 5 \log(r \Delta) + 2.5 \log[(1 - G)\Phi_1(\alpha) + G\Phi_2(\alpha)] \]

- \( H_V \) = absolute magnitude of the target
- \( V \) = apparent magnitude
- “\( R \Delta \)” = distance correction
- “\( G \Phi \)” = phase function

\[ R = 665 \text{ km} \times 10^{-H_V/5} \ p_V^{1/2} \]

- \( R \) = target radius

\[ \pi R^2 (1 - A) S = \eta \varepsilon \sigma R^2 \int_{-\pi/2}^{\pi/2} \int_{-\pi}^{\pi} T^4(\theta, \phi) \cos \phi \ d\phi \ d\theta \]

Energy balance equation
Types of Simple Thermal Models

**Standard Thermal Model (STM)**

\[ T_{\text{Max}} = \left( \frac{S_0(1-A)}{\eta \varepsilon \sigma} \right)^{1/4} \]

- Equivalent to assuming thermal inertia \( \Gamma = 0 \) (instantaneous thermal equilibrium with insolation).
- Temperature distribution depends on the angle from the subsolar point, \( \theta \), as \( \cos^{\frac{3}{4}}(\theta) \).
- The "beaming parameter", \( \eta \), allows the model to be tuned to account for the effects of roughness, non-0 thermal inertia, rotation. Values \( \sim 0.5 < \eta < 2 \) are observed.

**Fast Rotator or Isothermal Latitude Model (ILM)**

\[ T_{\text{Max}} = \left( \frac{S_0(1-A)}{2\eta \varepsilon \sigma} \right)^{1/4} \]

- Equivalent to assuming thermal inertia \( \Gamma = \infty \) (nightside and dayside temperatures are equal).
- Temperature distribution depends on the latitude, \( \lambda \), as \( \cos^{\frac{3}{4}}(\lambda) \), and is lower than for the STM.
- The beaming parameter rolls up effects such as thermal inertia, roughness, and finite rotation, similarly to the STM.

See e.g. Harris, Icarus 1998
Thermophysical Models (TPM)

- TPM accounts for
  - Diurnal insolation variations
    - Spin \textit{vector}
  - Subsurface conduction (\( \Gamma = \text{thermal inertia} \))
  - Surface roughness
    - Parameterized as RMS slope
    - Roughness causes localized temperature enhancements, enhanced emission at small phase angles
  - Actual viewing geometry
- Finite element approach
  - Model predicts \( T(x,y,z) \)
  - Can incorporate inhomogeneous properties
    - Albedo, thermal inertia, ...
  - Can account for non-spherical objects
- Results give direct physical insights
  - Application requires knowledge of, or assumptions about, multiple target properties

See, e.g., Spencer, Icarus 1990
The STM and ILM give results for $p_V$ and $D$ as accurate as results from thermophysical models (TPM).

Extensions to these account for viewing at non-zero phase angles (e.g. NEATM) and sub-observer latitude.

The ‘beaming parameter’ has no direct physical interpretation (but see previous chart).

There are fewer STM / ILM free parameters than for the TPM. Given that there are usually only a few thermal data points ($1 - 3$ in most cases) in the simpler models are in some ways preferred.

$$T_{Max} = \left(\frac{S_0(1-A)}{\eta \varepsilon \sigma}\right)^{1/4}$$

$$T_{Max} = \left(\frac{S_0(1-A)}{2 \eta \varepsilon \sigma}\right)^{1/4}$$
Converts geometric albedo to bolometric albedo, which is used for calculating energy balance.

$$q = 0.336 \, p_V + 0.479$$

Brucker et al. 2009
Absolute Magnitude: Size and Albedo
Absolute Magnitude: Size and Albedo

![Graph showing the relationship between absolute visual magnitude ($H_v$) and diameter (km)]
Beware of HV from MPC, Horizons

H magnitudes from these services are biased \(~0.25\) mag too bright, on average...
A visual magnitude measurement constrains the albedo and diameter to lie somewhere along this line. This example is for HV = 5.4.
The spectrum of an object consists of a reflected and emitted (thermal) component.

In these examples the STM beaming parameter is set to limiting values of 0.6 and 1.9.

This STM fit to a 25µm flux density results in large uncertainties on $pV$ and $D$. However, the slope of the spectrum < 30µm, dominated by emission from the warmest areas on the target, is well represented.
This STM fit to a 70um flux density produces smaller uncertainties on \( pV \) and \( D \), but leaves large uncertainties regarding the emission from the warmest areas on the target.
This STM fit to a 200um flux density produces useful constraints on pV and D, but not on the emission at shorter wavelengths.
Uncertainties on the fitting parameters depend on the wavelength of the thermal measurement relative to the wavelength of the peak of the thermal emission.
STM Fits using two Thermal Fluxes

Fits to more than one thermal wavelength provide a direct measurement of the ‘color temperature’ of the emission, producing much smaller uncertainties on D and $p_V$. 

Beam = 1.18 - 1.92
Diam = 264 - 236
$p_V$ = 0.18 - 0.22
Solution using:
- 25um Flux Density
- 70um Flux Density
- 200um Flux Density

25um + 70um with 5% errors
beam = 1.18 - 1.02

beam = 1.9

D = 250km
\( p_Y = 0.2 \)
beam = 1.1
TNO Albedos and Sizes: *Spitzer* Results

Stansberry et al. 2008
32 objects
Spitzer 24um & 70um

Open points: Centaurs
Filled points: TNOs
Note that red ≠ dark, at least for cold-classical TNOs…
Beaming Parameter for TNOs

Herschel + Spitzer
Herschel only
Spitzer only

Beaming factor

Heliocentric distance (AU)

Lellouch 2013
Fig. 2. Beaming factor $\eta$ as a function of **Left:** geometric albedo and **Right:** diameter. Labels M, H, TX, E, Q refer to Makemake, Haumea, 2002 TX$_{300}$, Eris and Quaoar, respectively.

Lellouch 2013
Thermal Inertia from Beaming for TNOs

Fig. 11. Beaming factor $\eta$ as a function of heliocentric distance $r_h$ for the entire sample, compared with Monte-Carlo simulations assuming a rotation period of 8 h, a geometric albedo of 0.1, a uniform distribution of the polar axes on the sphere, and a random distribution of surface roughnesses. Thermal inertia $\Gamma = 1, 2.5$ and 8 MKS cases are shown here. Although $\Gamma = 8$ MKS may seem needed to account for the three points with $\eta = 1.5$-1.8 at 13-18 AU, this case underpredicts the number of small $\eta$ values at $r_h > 25$ AU, and $\Gamma = 2.5$ MKS provides the overall best fit.
TNO Composition
Spitzer/IRAC Composition Constraints

IRAC 3.6 & 4.5 micron photometry + vis & nIR

- Silicates, H2O, different kinds of organics can be differentiated
- Molecular ices can as well (N2, CO, CO2, CH4)

Figures courtesy of N. Pinilla-Alonso, in prep.
Spitzer/IRAC: K/3.6/4.5 Composition Map

Figures courtesy of N. Pinilla-Alonso, *in prep.*
See also dalleOre 2015.

- Ice components map into unique regions in K + IRAC color/color space

- Much more Spitzer data available
  - ~50 KBOs + Centaurs w/ decent IRAC colors
TNO Dwarf Planet spectra are dominated by molecular ices.

They, too, are red in the optical, probably due to organics (except Haumea?)
Resolved Satellite Imaging: NIRCam

- Well-resolved satellites
- $160^2$ subarray bright limits
Satellite Photometry with NIRCam

- 400^2 subarray bright limits

- 1000 second exposure sensitivity
Activity in Distant Comets and Centaurs

Figure 1: Spitzer/IRAC images of comet C/2013 A1 (Siding Spring) taken 2014 March 26 ($r_h=3.1$ AU, 30-s exposures, 47 repeats, Galactic latitude = -65 deg). Top left: 3.6-µm median-combined mosaic (dust). Top center: 4.5-µm median-combined mosaic (dust+gas). Top right: 4.5-µm gas coma after dust subtraction. Bottom row: the same images, but after subtracting the shadow observation (i.e., stellar background). The shadow observation greatly improves the data quality. The derived gas fluxes are similar for the two techniques, but our ability to examine the morphology of the coma in the original data is nearly lost due to background contamination.

No background Subtraction

W/ background Subtraction

3.6µm: Dust 4.5µm: Dust+Gas 4.5µm: Gas Only

Courtesy of Mike Kelley, UMD
Cometary Nuclei with NIRSpec & NIRCam

- Comets can be studied through the 1-5 um region
- High sensitivity (1000 sec sensitivities shown)
- At distances where H2O is unlikely to drive activity
Simulated Comet Spectra

**Milam et al. 2016**

Unique spectroscopy with JWST
NIRSpec simulation (RP ~ 3000)

- Water \( \text{H}_2\text{O} \)
- Methane \( \text{CH}_4 \)
- Ethane \( \text{C}_2\text{H}_6 \)
- Carbon dioxide \( \text{CO}_2 \)
- Carbonyl sulfide \( \text{OCS} \)
- Carbon monoxide \( \text{CO} \)
- HCN
- Acetylene \( \text{C}_2\text{H}_2 \)
- Methanol \( \text{CH}_3\text{OH} \)
- Formaldehyde \( \text{H}_2\text{CO} \)
- Deuterated Water \( \text{H}_2\text{O} \)

**Wavelength [microns]**

- 2.5
- 3.0
- 3.5
- 4.0
- 4.5
- 5.0

**Observable flux**

**9P/T1 Deep Impact**

A’Hearn et al. 2005
KBO Spectroscopy with NIRSpec

JWST Spectroscopy: 1000 sec Continuum Sensitivity

Spectrally Interesting KBOs

Pluto: CH₄
Haumea: H₂O
Orcus: H₂O
Eris: CH₄
Sedna: CH₄, H₂O

10σ NEFD; Flux Density (μJy)
Wavelength (μm)

8/31/2016
KBO Thermal Radiometry with MIRI

- MIRI can measure temperature distributions for quite small KBOs
- Sensitivity well matched to that of ALMA
- Valuable for
  - Thermal inertia
    - Composition
    - Regolith structure
  - Emissivity
  - Albedo
  - Diameter
JWST Capabilities: Giant Planets Imaging

- **NIRCam Subarrays**
  - short integration times
  - Significant FOV
  - Simultaneous 0.6-2.3 (shortwave) and 2.4-5 (longwave) coverage
    - Matched FOVs
  - Smaller subarrays available: 640² (shown), 320², 160²
  - Dithers fill detector gaps in the short-wave channel
Giant Planet Imaging with NIRCam

- Bright limits for 640x640 subarrays
- 160x160 limits are 15x higher
- Bright limits for 64x64 subarrays (6.4” FOV)
- MIRI IFU spectroscopy limits are ~100x higher
Giant Planet Spectroscopy: NIRSpec IFU

![Graph showing surface brightness versus wavelength for different planets and modes of operation.](image)

- **Jupiter**
- **Saturn**
- **Uranus**
- **Neptune**

**Axes:**
- **Y-axis:** Surface Brightness (Jy/sq.arcsec)
- **X-axis:** Wavelength (μm)

**Legend:**
- **R = 2700, FULL-FRAME mode**
- **R = 1000, FULL-FRAME mode**
- **R = 30–300, FULL-FRAME mode**
- **R = 30–300, STRIPE mode 512×2048**
PASP Special Issue
(Jan 4, 2016)
Innovative Solar System Science with the James Webb Space Telescope
Stefanie Milam, Special Editor

11 topical papers
1 high-level paper (Norwood et al.)
10 JWST Solar System Focus Groups

- **Asteroids** (Andy Rivkin, JHU/APL)
- **Comets** (Chick Woodward, U. Minnesota)
- **Giant Planets** (Jim Norwood, NMSU)
- **Mars** (Geronimo Villanueva, GSFC)
- **NEOs** (Cristina Thomas, GSFC)
- **Occultations** (Pablo Santos-Sanz, IAA-CSIC, Spain)
- **Rings** (Matt Tiscareno, Cornell)
- **Satellites** (Laszlo Kestay, USGS)
- **Titan** (Conor Nixon, GSFC)
- **TNOs** (Alex Parker, SwRI)
- **JWST Solar System Capabilities** (Milam, GSFC)
How will we Continue to Explore TNOs?

JWST and future space-based (SPICA? FIRST? UVOIR?) and large ground-based observatories will be the way.