Ices on Minor Planets and Dwarf Planets as Seen Through Gemini

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Outline

• Part 1 - The Outer Solar System
  • Dynamical history of the Solar System
  • Distant ices - the Kuiper Belt Objects
• Part 2 - Time domain Solar System studies
  • Nearby ices - the Main Belt Comets
  • Gas giants and their moons
  • Near Earth Asteroids
  • Binary Asteroids and Kuiper Belt Objects
  • Occultations
Why Study the Kuiper Belt Objects?

- KBOs are the most distant bodies in the solar system (30 AU - 1000 AU)
- KBOs are the coldest bodies in the solar system (30K - 50K)
- KBOs retain a dynamical history of early events in the solar system (orbits)
- KBOs are the most likely population to retain a physical history of the early solar system (ices)
The Outer Solar System - Orbits
The Outer Solar System - Orbits

The diagram shows the distribution of objects in the outer solar system, plotted as a function of semimajor axis and eccentricity. Different colors represent different types of objects, such as classical KBOs, Plutinos, scattered KBOs, 2:1 resonant KBOs, and Centaurs. The perihelion is marked at 30 AU.
The “Nice” model suggests that the gas giant planets switched positions in the early solar system (2005 Tsiganis et al).
The Outer Solar System - Orbits

Tsiganis, Gomes, Morbidelli and Levison (2005)
The Outer Solar System - Orbits

Tsiganis, Gomes, Morbidelli and Levison (2005)
The “Nice” model successfully* explains the current observed structure of the Kuiper Belt. 

*more successfully than any other model

Model

Data

Nice, France

2007 Morbidelli, Levison and Gomes

The Outer Solar System - Orbits
Largest known trans-Neptunian objects (TNOs)

- Eris
- Sedna
- Orcus
- Pluto
- Charon
- Quaoar
- 2005 FY₉ (Makemake)
- 2003 EL₆₁ (Haumea)
- Varuna
The Outer Solar System - Ices - Haumea

Water

2007 Trujillo et al.
The Outer Solar System - Ices - Eris

Methane

Eris

Pure Methane Ice (1 mm)

Pluto (Brown and Calvin 2000)

Relative Reflectance

Wavelength [microns]

2005 Brown, Trujillo and Rabinowitz
The Outer Solar System - Ices

Which minor planets are known to have ice?

**Water-dominated spectra:**
(1) Charon, (2) Haumea family members (8 known), and (3) Orcus

**Methane-dominated spectra:**
(1) Pluto, (2) Eris, and (3) Makemake

Mixed absorptions:
Quaoar, Triton, others.

Neutral / Weak (<10%) absorptions:
About 2/3 of observed bodies including Pholus, Sedna, others
The Outer Solar System - Ices

A simple physical model of the bodies explains compositions except for Haumea (2003 EL61)

2007 Schaller and Brown
Where are the Ices?

• Simple theory suggests that only large bodies should have methane.

• Previous works have not taken spectra in a consistent manner.

• We decided to test this at Gemini and Magellan using a custom set of photometric filters sensitive to water ice and methane ice.

• Ices are neutral in the visible, so the near-infrared is the place to look. (The mid-IR is ideal, but objects are faint enough to make this difficult.)
Observations:

Magellan:
- Two observing runs (Oct 2008, Apr 2009).
- Collected 1800 images over 3 good nights.
- Observed about 25 objects, averaging about 1.5 hours per object.
- Repeated J-band imaging to correct for lightcurve effects.

Gemini North:
- About 3800 images of queue data collected
- About 65 objects observed, averaging 1.25 hours per observation.
- Objects with low signal are repeated if needed.

Analysis:
- First pipeline is finished, some minor tweaks are going to be made
Proof of Concept:

We correlated published KBO spectra (symbols) with our filter photometry.

We see 1 to 2 magnitudes difference between ice types.

Our custom infrared filters discriminate between basic surface types.

Icy: Haumea+family, Orcus, Ixion, Makemake, Eris.

2011 Trujillo, Sheppard and Schaller
Do the Haumea Family Members show a correlation between absorption and size?
Yes (4 sigma).

You might expect this from a catastrophic origin of a differentiated body — the small objects are from the shattered exterior and have more ice. Alternatively, grain size could also play a role.

2011 Trujillo, Sheppard and Schaller
Are the non-Haumea Icy objects from a particular dynamical class?
No.

Water Objects:
Orcus (3:2)
Ixion (3:2)

Methane Objects:
Makemake (Classical Hot)
Eris (Scattered)

We are currently analyzing the latest batch of data.
Final results coming soon...

2011 Trujillo, Sheppard and Schaller
Summary of Part 1

-We are conducting the first systematic photometric survey for KBO ices. Final sample is about 90 KBOs brighter than V=22 (K ~ 20.5). All data are collected.

-2009 YE7 is a newly discovered Haumea family member. It and the other Haumea family comprise the strongest water ice absorption in the outer solar system. (Collisional family ~1 Gyr old)

-Haumea’s progeny have deeper absorption than Haumea (4 sigma). (Collisional differentiation)

-Strong methane absorption is preferentially correlated with largest bodies to (~3 sigma) confidence, even if taking probable albedo effects into account. (Methane is unstable on small bodies.)

- Non-Haumea water ice bodies are neither systematically large nor highly inclined nor from a particular dynamical class. (For more, see 2011 Trujillo, Sheppard and Schaller)

-We are continuing the survey to probe the fainter KBOs, where the strength of photometry really lies. We will see if any correlations exist between dynamical parameters (i.e. orbits) and surface characteristics (the presence of ices).
Main Belt Comets

Gas-Driven MBC, 133P/Elst-Pizarro (Hsieh, Jewitt, Fernandez 2004)

Dust-Driven MBCs
Jewitt et al. 2011
Jewitt et al. 2010
Pan-STARRS I
Discovery of MBC P/2006 VW139

a) 2011 Aug 30 (PS1)
b) 2011 Nov 5 (Discovery, PS1)
c) 2011 Nov 14 (UH 2.2m)
d) 2011 Dec 4 (NTT)
e) 2011 Dec 19 (UH 2.2m)
f) 2012 Jan 7 (LOT)

(P/La Sagra, Keck)

(P/2006 VW139, GMOS)

This algorithm is based on a stochastic approach to find the best image reconstruction, using information about both the object and the Point Spread Function (PSF). The inset in Fig. 4 shows the impact site after deconvolution. Fig. 5 shows an image of the impact site at 5 µm, a wavelength sensitive to thermal emission from warm layers in Jupiter’s atmosphere. Panel (a) shows an image of that part of Jupiter that contains the impact site; panel (b) shows the same image after deprojection, with the deconvolved 1.65-µm image from Fig. 4 superposed. On 25 July we could use Io for wavefront sensing when the impact site was visible (Fig. 6). As in de Pater et al. (2010) typical resolutions in AO images of Jupiter at 1–2 µm are roughly 0.12–0.16 (350–480 km at Jupiter’s distance); the resolution in our 1.65-µm non-AO image is 0.35.

All images were processed using standard near-infrared data reduction techniques (flat-fielded, sky-subtracted, with bad pixels replaced by the median of surrounding pixels). The geometric distortion in the images was corrected using the “dewarp” routines.
Overall volcanic activity changed much: in 2010 a few bright eruptions: Loki and Kanehekili; note also Pele, and Mulungu Patera.

Volcanism on Io - Time Variable

2.2 μm

3.6 μm (Marchis et al. 2005)

(preliminary, de Pater et al in prep)
Volcanism on Io

Gemini images of Io under excellent conditions. Left: BrGamma, Right: Lp bands. Center volcano is Pele.

Altair/NIRI observations de Pater et al (in prep.)
Uranus clouds

Fig. 2. WFC3 F845M 2011 images on October 13 (A) and 23 (B) reveal that a substantial increase in spot brightness had occurred prior to the H filter “discovery image” (C) made by the Gemini NIRI camera on 26 October 2011.

The Uranus clouds change rapidly, and are likely companions to vortex circulation (Sromovsky et al 2012)
Neptune has a very dynamic atmosphere.
YU55: Gemini mid-IR Observations

- Medium-band photometry in 6 bands
- Span thermal emission peak

2005 YU55 was moving ~3 deg/hour during these observations

Moskovitz et al., Carnegie (2012)
YU55: Thermo-physical Model

With size uncertainty: $\Gamma \sim 500-1500$

Moskovitz et al., Carnegie (2012)
YU55: Surface Properties

YU55 Thermal inertia $\sim 500-1500 \text{ J m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$

- Eros $\sim 170 \text{ J m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$  
  (Harris & Davies 1999)
- Itokawa $\sim 750 \text{ J m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$  
  (Mueller et al. 2007)

Sub-solar temp.  
1.0 AU  
$T_{ss} \sim 400 \text{ K}$

At perihelion  
0.65 AU  
$T_{ss} \sim 500 \text{ K}$

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Moskovitz et al., Carnegie (2012)
2012 DA14: Small and CLOSE

Discovered Feb. 23, 2012 by the La Sagra Sky Survey in Spain

40m asteroid to pass at ~5R⊕ on Feb. 15, 2013

10th closest fly-by ever

First time such an encounter is known in advance

Moskovitz et al., Carnegie (in prep)
DA14: Pre-encounter Spectroscopy

- Visible spectroscopy with GMOS/Gemini on Mar. 2, 2012
- Taxonomy: Ld-type; Spectral analogs = igneous rocks

Moskovitz et al., Carnegie (in prep)
NIRI/Altair observations of asteroid binaries lead to mass/density measurements of asteroids
Marchis et al. (AGU, 2012)
GMOS in excellent seeing

Constraining KBO orbits for equal-sized wide binaries

Alex Parker (HIA/Harvard) et al. 2011

$\Delta 1.1''$  $\Delta 1.6''$

$\Delta 1.1''$  $\Delta 1.2''$

Figure 1. Example of Gemini data and PSF fit. Top left: original image from the GMOS camera of 2001 QW$_{322}$. Bottom left: synthetic PSF model of binary components. Top right: image residuals after subtracting binary and other point sources in the image. Bottom right: relative contributions of both PSF components. Same stretch is applied to all images, and flux scaling is linear.
Predicted Quaoar occultation
July 10, 2012 UT

~1 arcmin motion in 1 day

(Wes Fraser at HIA, in prep)
Preliminary Photometry of “near-miss” (~50 mas) (July 10, 2012)

(Wes Fraser at HIA, in prep)
• A recent quote from one of our Queue Coordinators regarding the occultations:

“Your solar system objects are really annoying to schedule. Maybe you want to trying looking at some galaxies instead.”

Posters

• Henry Roe (Titan)
• Will Grundy (KBO binaries with Laser AO)
Recap

• Part 1 - The Outer Solar System
  • The gas giants switched places in the early solar system. Observational evidence is imbedded in the KBOs
  • Ices on the KBOs - Compositions are consistent with simple physical model of volatile loss. The Haumea family is consistent with a collisional origin.

• Part 2 - Time domain Solar System studies
  • Nearby water ice - the Main Belt Comets
  • Gas giants storms, and moon volcanism probe internals of planets
  • Near Earth Asteroids are tricky to observe, but yield detailed physical information
  • Binary Asteroid and Kuiper Belt Object orbits are the only way we can obtain masses
  • Occultations can place constraints on KBO atmospheres