“TNOs” or “KBOs”

- Kuiper’s original prediction: objects were scattered to the Oort cloud by Earth-sized Pluto
- did not think the objects presently existed

- Edgeworth, Leonard, Whipple, and others made similarly vague claims
- none made accurate, precise predictions

- observations do not support a single class of objects
**TNOs**

**Definition:** a > 30 AU, not a comet or in Oort Cloud

**First:**
- Pluto … 1930 … D = 2368 km
- Eris … 2003 … D = 2326 km

**Brightest:** Pluto

**Oddballs:** Haumea, Sedna

**Surfaces:**
- variable atmospheres (?) sublimation+organic haze
- diverse ice organic solids
TNOs

- a > 30 AU, most have perihelion > 30 AU
- various dynamical classes
- flattened torus … not disk … z =10 AU @ a~50 AU
- source of Centaurs, Jupiter (short period) comets, some outer moons

- Pluto discovered 1930 … QB₁ discovered 1992
- > 1000 discovered, at least 70,000 > 100 km thought to exist (Jewitt)

- volatile ices that survived formation epoch (4.5 Gyr)
- 4% multiplicity
Largest known trans-Neptunian objects (TNOs)

- Dysnomia
- Nix
- Charon
- Hydra
- Namaka
- Hiʻiaka
- Eris
- Pluto
- Makemake
- Haumea
- Sedna
- 2007 OR₁₀
- Weywot
- Quaoar
- Orcus
- Vanth
1. Classical KBOs

- between 2:3 (39.5 AU) and 1:2 resonances (48 AU) but not including those
- two dynamical classes
  - "cold" e < 0.1 and i < 10°
  - "hot" e larger and i up to 40°
- cold (in situ/near Neptune) are redder than hot (near Jupiter)
2. Resonant Objects

- mean motion resonance with Neptune
- “Plutinos” at 2:3
- dynamically stable
3. Scattered Disk Objects

- ~35 to 40 AU
- source of Jupiter family comets
- flung out when Neptune migrated outward
- high eccentricity and inclination

- first 1996 TL$_{66}$ ... a = 89 AU, e = 0.58, i = 24°
- also Eris ... a = 68 AU, e = 0.44, i = 44°
- scattered and being depleted OR in higher order resonances and somewhat stable
4. Detached Objects

- extended scattered disk/inner Oort Cloud objects
- resonances: 1:3, 2:7, 3:11, 5:22 and 4:79 and more

- Sedna ... $a = 524$ AU, $e = 0.85$, $i = 12^\circ$
- 2000 CR$_{105}$ ... $a = 230$ AU, $e = 0.81$, $i = 23^\circ$

- could not have been emplaced via Neptune ... passing star?
Sedna

- $P \sim 12,000$ yr
- $e = 0.85$
- $a \sim 524$ AU
- $ap \sim 975$ AU
- $pe \sim 75$ AU
Oort Cloud

- current TNO aphelia record: 2000 OO$_{67}$ at 1014 AU
- probably is not a distinct boundary to Oort cloud
- source of Halley family comets
Nice Model  

Tsiganis et al. (2005) and Gnomes et al. (2005)

- (left) before Jupiter/Saturn 2:1 resonance
- (mid) scattering of Kuiper belt objects into the solar system after the orbital shift of Neptune
- (right) after ejection of Kuiper Belt bodies by Jupiter
- Neptune migration of \(~7\) or \(8\) AU over 10 Myr could account for the resonant populations
- scattered disk explained by long term perihelic interactions with Neptune
- accounts for late heavy bombardment period at 3.8-3.9 Gyr
- explains Hot but not Cold classical KB
- alternative is scattering and chaotic capture by an eccentric Neptune (Levison et al. 2008)
red: trojans 4,079
yellow: centaurs 184
white: plutinos 220
cyan: other resonant TNOs 24
green: cubewano 824
magenta: SDOs 139
red: trojans
green: TNOs
yellow: centaurs

Kuiper Cliff
Real edge or gap?

2:3
1:2
2:5
Eris
Makemake
Pluto
Haumea

red: trojans
yellow: centaurs
green: TNOs
Compositions

- very faint … even for 8-10m class telescopes
- low temp (< 50K)
- low density (1-2 g/cm$^3$)
- colors (phot for ~few hundred, classification)
  … grey to very red
- composition (spec for a handful)
  … CH$_4$ (on 3 largest TNOs), NH$_3$, H$_2$O, N$_2$, CO
  … similar to comets
- outgassing, impacts, radiation processing, cryovolcanism? (resurfacing and methane replenishment)
Colors

- Centaurs bimodal
- TNOs unimodal
- mixed population?
- color range from composition?
  but low temp range
- same initial composition and processed over time?
- collisions?
- reddening
- young surface creates high albedo
Spectra
O-H, C-N, N-H molecular bands apparent, H$_2$O and CH$_4$ in largest KBOs influenced by physical state and grain size, shape, and temperature from Jewitt and Luu (2004)

crystalline (not amorphous) ice heated $> 110$ K
  - radioactive decay?
  - impacts? $\rightarrow$

crystalline ice is recent or replenished (10 Myr)

Quaoar

crystalline ice feature
(1.65 microns)

H$_2$O ice

strong absorption by Earth atm
Pluto

- Pluto + Charon: $1.5 \times 10^{22}$ kg
  - 20% of mass of Moon
- 5(+) moons in system
  - formed by glancing impact?
- density $\sim 2 \text{ g cm}^{-3}$ (70% rock)
- non-isothermal (T $\sim 30-60$)

- CH$_4$ + N$_2$ atmosphere $\sim 1-30$ microbar and shifts
  - low gravity ... rapid atmospheric hydrodynamic escape
- steep drop in occultation flux near surface
  - thick surface haze? high temperature gradients?

- uneven albedo
- solid N$_2$, CH$_4$, H$_2$O, CO ices
  - bright: N$_2$ and H$_2$O ices
  - dark: tholins?
    - cryovolcanism?
    - UV processed CH$_4$
      - seasonal deposits?
Triton

- retrograde orbit … captured during Neptune’s migration?
- 40% surface imaged … 60% silicates, 40% ices
- density ~2 g/cm³
- T ~ 40K (variable)
- 8 km plumes, dark deposits, N₂ winds
  photolysis produced hydrocarbons
- cryovolcanism, “subsurface greenhouse effect”
  clear ice over dark substrate, 4K increase could produce 8 km p
  plumes which last 1 yr or more
  Soderblom et al. (1990)
Eris (2003 UB₃₁₃)

- SDO, 557 yr period
- V=18.7, R=18.3

- diameter
  Spitzer: 2600-3400 km
  HST (Brown et al.): 2300-2500 km (barely resolved)
  occultation: 2326 +/- 12 km (Pluto is 2360)
  density 2.5 g/cm³ ... mostly rocky
  most massive TNO … 27% > Pluto

- 96% albedo! (most TNOs 10-20%)
- methane dominated surface, like Pluto but less red
  ~30 K, methane is involatile … pure methane ice
  may become volatile and mix as approaches the Sun

- similar to Pluto in size and appearance but very different on the inside
Orbit of Eris (136199 Eris)

- Perihelion: 37.77 AU
- Aphelion: 97.56 AU
- Eccentricity: 0.44
- Inclination: 44°
- Orbital period: 557 years

11 October 2006
Solar System Explorers 11

Name a minor body with semimajor axis greater than Mars’ orbit (1.52 AU) and describe three of its physical characteristics, e.g., Pluto has density 2.03 g/cm³ and is roughly 70/30% rock/ice by mass, where the ice is primarily N₂.

1. 2687 Steins – in MB has chain of 7 craters, 3x2km, albedo 0.35
2. 243 Ida – density 2.2-2.9 g/cm³, magnetic material, chondrite/meteor-like composition
3. 16 Psyche – 253km, density 6.7 g/cm³, primarily Fe/Ni content
4. 10 Hygiea – 2% mass of MB, many kg, density 2 g/cm³, 500x400x400km
5. Fortuna – density 2.7 g/cm³, tholins on surface, carbonaceous G type
6. Eris – second highest albedo in SS, CH4 ice, diameter comparable to Pluto
7. 55576 Amicus – Centaur, albedo 0.18, 76km, H = 7.4
8. Sedna – one of reddest objects … tholins, 12K, albedo 0.3
9. Kleopatra – shaped like dog bone, Fe/Ni, interior is likely rubble pile
10. Pallas – 7% mass of MB, silicate surface, larger than Vesta but less massive
11. 41 Daphne – overall density 1.95, but surface density is 2.4
12. Temple 1 – density 0.62, comet hit by Deep Impact, hydrocarbons, H₂O buried beneath dusty crust
13. Hale-Bopp – sodium tail, smallest dust grains from any comet, 2X deuterium abundance oceans
14. Makemake – code name is Easter Bunny, minimal/no atmosphere
15. Haumea – fastest spinning object in SS at 4 hours
16. …
17. …
18. …
19. …
20. …
Name a minor body with semimajor axis greater than Mars’ orbit (1.52 AU) and describe three of its physical characteristics, e.g. Pluto has density 2.03 g/cm$^3$ and is roughly 70/30% rock/ice by mass, where the ice is primarily N$_2$.

1. Mr. Rogers – 2.34 AU, e 0.34, H 12.6
2. Haumea – 1/3 Pluto mass, ellipsoid ~ E5 … because of rapid rotation
3. Pallas – d 545 km via occultation, a 0.16, Tholen spectral type B (not a C or S)
4. Ixion – 650x822 km, 3e20 kg, 2.0 g/cm3, .434 km/s escape v
5. Vesta – 3.9 g/cm3, 520 km, pyroxenes on surface
6. Sedna – almost as red in Mars (via SMARTS!), d 1600 km, methane and water ices
7. Triton – cryovolcanism, retrograde orbit, cantaloupe terrain due to tidal stress upon orbital entry
8. Psyche – 2.92 AU, nearly pure Fe/Ni, from a parent body but now an orphan
9. Ceres – 41% mass of Main Belt, d 950 km, water/carbonates on surface
10. Ceto – 174 km, 1.37 g/cm3, crystallized ice on surface via companion
11. Enceladus – 100% reflectivity, geysers of water+, creates E ring
12. Eris – most massive KBO KNOWN, a 0.96?, methane ice
13. Asbolus – impact crater less than 10 Myr, 84 km, H 9
14. Hilda – 2:3 resonance with Jup, occulted a star in 2002, H 7.5
15. Quaoar – 43.6 AU, crystalline ice due to recent heating, moon created by Mars hitting
16. …
17. …
18. …
19. …
20. …