The Kuiper Belt, and the Early Evolution of the Outer Solar System

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What is the Kuiper Belt?

- a vast swarm of giant comets orbiting just beyond Neptune
  - debris that failed to coalesce into another planet
- nomenclature isn’t settled: Kuiper Belt, Edgeworth–Kuiper Belt, Trans–Neptunian Belt, etc.
- members are: KBOs, EKOs, TNOs, etc.
1992 QB1: the first known KBO?

- discovered in 1992 by David Jewitt & Jane Luu
- $m = 23$ at $r \sim 45$ AU
- apparent motion of $3''$/hour on sky due to parallax from Earth’s orbital motion

...or was the first KBO discovered in 1930 by Clyde Tombaugh?
What does a KBO look like?

- KBOs are distant, ice–rich debris that were left over from when Solar System first formed.

- likely heavily cratered due to impacts w/other KBOs, 
  \(\Leftarrow\) perhaps like Phoebe?
  – which is NOT a KBO...

- nonetheless, this pic’ of Phoebe might be a representative of a typical KBO

from CICLOPS: Cassini Imaging page.
Kuiper Belt Statistics

- Approximately 1000 known KBOs
- Observable population has $20 \lesssim D \lesssim 1000$ km, masses $< \frac{1}{5} M_{\text{moon}}$
- Estimated population: $N(D > 100\text{km}) \sim 200,000$
- Total mass $M \sim 0.02 M_\oplus$
- Approximately $10-100 \times$ asteroid belt

from the Minor Planet Center
Formation of planets, comets, asteroids...and the Kuiper Belt

- Planet formation is a by-product of star formation
- first, an interstellar cloud of gas & dust collapses due to its gravitational self–attraction
  - $\sim 99\%$ of the cloud forms young Sun
  - $\sim 1\%$ of the cloud forms a disk orbiting the Sun, the *solar nebula*
dust grains are concentrated in the solar nebula disk

- dust grains collide & stick to form larger objects

- over time, dust grow, form planetesimals (the building blocks of the planets)

regions where \( r \lesssim 5 \) AU, the nebula temperature \( T \gtrsim 200 \) K (about \(-70 \) C)

- these planetesimals are rock–rich, ice–poor (too warm!)
  - they will later collide & form the rocky terrestrial planets (M,V,E,M)
  - any left-over planetesimals will become asteroids that live at \( r \sim 3 \) AU

where \( r \gtrsim 5 \) AU & \( T \lesssim 200 \) K

- these cooler planetesimals are ice–rich
  - they will form the cores of the gas giant planets (J,S,U,N)
  - any left-over planetesimals will become comets in Kuiper Belt & Oort Cloud
KBO Accretion models

- KBO accretion models tell us:
  - the KBO ‘seeds’ were initially in nearly circular orbits
  - you need $\sim 30M_\oplus$ of matter in order to form Pluto–sized KBOs in 4.5 billion years

- current KB mass is $\sim 0.02M_\oplus$
  - the KB’s mass was depleted by factor of $\times 1500$!

- depletion due to collisions among KBOs?
  - collisions generate dust
  - dust is removed by starlight
    * radiation pressure
    or PR drag

Hubble Space Telescope image by Krist et al.
KBO Orbits—anything but circular!

- accretion models predict nearly circular orbits, ie, $e \approx 0$
- but astronomer find KBOs in orbits with eccentricities of $\sim 0.1–0.3$
- something has disturbed the Kuiper Belt since formation!
- note KBOs at Neptune’s 3:2
  - site where a KBO gets ‘kicked’ every 330 years
  - $e$’s get pumped up here
  - KBOs were ‘parked’ here
  * possibly due to planet migration
N-body simulations show that as Neptune migrates outwards,

- Neptune’s *resonances* can capture KBOs
  - this drags the captured KBOs outwards
  - pumps up their eccentricities $e$
- astronomers have detected many KBOs at Neptune’s 3:2, 5:3, 2:1, 5:2, etc, which suggests that Neptune’s orbit did expand outwards
How far did Neptune migrate?

- $e$-pumping at 3:2 varies with Neptune’s migration distance $\Delta a$.
- Achieving $e \sim 0.33$ at 3:2 requires Neptune migrating $\Delta a \approx 9$ AU.
Why would the giant planets migrate?

- cores of giant planets formed within a planetesimal disk
- planet–formation was likely not 100% efficient
  - residual planetesimal debris is left over
- recently–formed planets scatter the planetesimal debris, exchange \( L \) with planetesimal disk
- \textit{Nbody} simulations (Fernandez & Ip 1984, Hahn & Malhotra 1999, Gomes, Morby, Levison 2004) show planets evolve away from each other, ie, Jupiter inwards, Neptune outwards

\[ M_D = 30 \, M_\oplus \]

\[ \Delta a_{\text{Nep}} \approx 9 \, \text{AU} \] requires debris mass \( M_D \approx 30 \, M_\oplus \), enough to build \( \sim 2 \) more Neptune’s...planet formation was quite inefficient
Centaurs, and the origin of Short Period Comets

- Centaurs have $a < a_{\text{Neptune}}$ (eg, Pholus, Chiron, Nessus, etc)
- often found in KB surveys, due to their proximity to Sun
- Centaurs are escapees from the Kuiper Belt
  - model shows they pop out of resonances,
  - get scattered about Solar System by giant planets
- some Centaurs get tossed within $r \lesssim 2$ AU, where they become visible as an active, short-period comet (aka, a Jupiter-family comet)
What is a comet?

- a comet is an icy planetesimal, eg, a dirty snowball, composed of:
  - mostly water ice + trace CHON:
    - CO, CO$_2$, CH$_3$OH, HCN, NH$_3$, ... and dust

Comet Wild–2 photographed by Stardust
Why do comets have tails?

- comets travel in wide, looping orbits about the Sun

- when $r \lesssim 2$ AU of Sun, their icy surfaces sublimate (eg., boil off)
  
  - releases gas & dust into coma, a $r \sim 10^5$ km cloud

  - solar wind & radiation sweeps gas & dust into tail $\ell \sim 10^6$ to $7$ km

  - all this from a comet nucleus with diameter 1–10 km

- most comets reside at $r > 2$ AU, where they are inactive, so they are dark and unseen...
if Centaurs/Short–Period Comets come from the Kuiper Belt...

where do Oort Cloud comets come from?

- from within the donut hole...
  - they probably formed *among* the giant planets
  - who accreted some of the planetesimal debris there
  - but also flung icy planetesimals into wide orbits about the Sun
The Oort Cloud is *huge*

- Oort cloud comets can travel as far out as $r \sim 50,000$ AU, which is about 25% of distance to nearest star.
Do other stars have Kuiper Belts?
Short dust lifetimes imply unseen KBOs!

- star HD 141569
- circumstellar dust is quickly destroyed, perhaps in millions of years?  
  - due to collisions, radiation pressure, PR drag
- dust lifetimes are $\ll$ age of star
- must be an unseen source of dust orbiting star  
  - most likely culprit: KBOs that collide & generate dust
University of Hawaii

AB Aurigae Disk
PRC99-21 • STScI OPO • C. Grady (NOAO at NASA Goddard Space Flight Center) and NASA
Circumstellar Debris Disks
Hubble Space Telescope • ACS HRC

NASA, ESA, J. Krist (STScI/JPL), D.R. Ardila (JHU), D.A. Golimowski (JHU), M. Clampin (NASA/Goddard), H. Ford (JHU), G. Hartig (STScI), G. Illingworth (UCO-Lick) and the ACS Science Team
Summary

- the Kuiper Belt is a debris disk—a relic that was left-over from when the giant planets formed

- this Belt is interesting, since it appears to preserve evidence of planet migration
  - the KBOs trapped at Neptune’s resonances suggest that Neptune’s orbit expanded $\sim 30\%$

- the Kuiper Belt is also the source of the short-period comets, which are samples of the Solar System’s outer edge
  - interestingly, long-period comets from the Oort Cloud probably formed closer to the Sun that the short-period comets

- circumstellar dust-disks have been detected in orbit about many nearby stars
  - these disks are often interpreted as evidence for extra-solar Kuiper Belts
  - the warps & gaps seen in these disks also suggest the presence of unseen planets orbiting within