The Collisional Evolution of Trans-Neptunian Objects

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Overview

- Collisions are important for understanding current and primordial TNO population
  - Accretion (early, low-V collisions)
  - Collisional disruption (higher-V collisions)
  - Surface processing (high-V, non-disruptive collisions)

- Current population holds clues to what happened collisionally and dynamically
  - Size distribution and total mass of TNOs
  - Spectral properties
Collisional environment depends on dynamical environment

- Most work assumes in-situ formation of Kuiper Belt
- Recent dynamical models suggest that this was probably not the case
- Kuiper belt evolution tied-in with evolution of other populations, which can serve as constraints on KB evolution
Overview -- Continued

• Talk Outline:
  - Current observational evidence
  - Estimates of TNO strength
  - In-situ formation of Kuiper Belt
    • Results from accretion modeling
    • Results from models of collisional grinding
  - Recent dynamical models and implications for collisional modeling (and vice versa)
Collision-related issues discussed in other talks:

- Correlation between spectral and orbital properties
  - Talk by Peixinho on Friday
Observational Evidence

- There are several observables that can be used to constrain models of TNO collisional evolution
  - Total mass of TNO population
  - Size distribution of TNO population
Mass of TNO Population

- Weissman and Levison (1996) - 0.1-0.4 Me
- Gladman et al. (2001) - ~0.1 Me
- Bernstein et al. (2004) - 0.01-0.1 Me

Lower than expected from a minimum-mass solar nebula by factor of 100-1000 or more.
Size Distribution of TNOs

- **Large bodies (~100 km and above)**
  - Trujillo et al. (2001) : $q = 4$ (+/- .5)
  - Gladman et al. (2001) : $q = 4.4$ (+/- 0.3)

- Too steep to be collisionally relaxed
  => Must be primordial

- **Slope must flatten at some size**
  - Otherwise, infinite mass
Bernstein et al. (2004) found:

- Different $q$ for 'classical' and 'excited' populations
- Slope flattens above $R=24$
  ($D \sim 100$ km)
• Petit et al. (2006) KBO survey found:
  – No statistical evidence for rollover around $R=23-25$

• Must flatten at some point
  – Likely $\sim 50$ km or below
Rollover in size distribution potentially a signature of collisional erosion
- More collisional erosion = rollover at larger diameter
- Could also just be an accretional signature
Strength of TNOs

- Many lab experiments
  - ~10 cm targets
  - Solid ice and porous or 'snowball' targets
  - $Q^* \sim 10^5 - 10^6$ erg/g

- Porous bodies not necessarily weaker, and may be stronger than solid bodies

Ryan et al. (1999), Arakawa et al. (2002), Burchell et al. (2002), Giblin et al. (2004)
Strength of TNOs

- Response of large, gravity-dominated TNOs (>100 m) to impacts is not well-constrained
  - Benz and Asphaug (1999) hydrocode models for solid ice
  - Predicts stronger small targets than lab experiments
Strength -- Continued

• Hydrocode simulations for large porous bodies needed!
  - Large rubble-piles or micro-porous bodies could behave differently than solid targets

NOTE: Asphaug and Benz (1996) SL-9 breakup modeling implies very weak bodies...
  - ONLY at tidal loading rates
  - NOT in conditions occurring during impacts!
Modeling of In-situ Formation

- Most modeling assumes that the Kuiper Belt formed in its present location

- Accretion of TNOs
  - Can they form in the first place?

- Subsequent collisional grinding
  - Can it reproduce current mass?
  - Can it reproduce the size distribution?
Accretion of TNOs

- To accrete large bodies (>100-km scale) between 30 and 50 AU:
  - Need 10-50 Me of material
  - Tens - hundreds of Myr
  - Low eccentricity (<0.01)

- May require Neptune to form late to keep e low
  - Most recent models can form large TNOs in <100 Myr

Slope of the primordial population
- $q \sim 4-4.5$ for larger bodies
- Consistent with observations

Primordial TNO population was 100-1000X more massive than today

?? Where did the mass go??

Kenyon and Luu (1999)
Collisional Grinding

• Collisions have been proposed to
  - Reduce the primordial TNO population to its current mass
  - Shape the current size distribution (eg. turn-over point)

• Significant collisional activity starts when
  - Bodies grow large and start exciting others
  - Neptune forms (excites out to ~50 AU)

Kenyon and Bromley (2004), Pan and Sari (2005)
Collisional Grinding -- Continued

- Does it work?

Simulations for Kuiper Belt...

Stern and Colwell (1997)

Kenyon and Bromley (2004)
Collisional Grinding -- Continued

- Mass can be reduced significantly by collisional grinding, but:
  - Requires most mass to be in small bodies
  - May require weak bodies
  - Still can't explain all mass loss
  - Some dynamical loss mechanism still needed

- Region beyond ~50 AU would experience little mass loss
  - If there was material there in the past, there should still be a lot now
Collisional Grinding -- Continued

- All simulations and analytical models find break in size distribution < ~100 km diameter
  - Kenyon and Bromley (2004) ~1-30 km
  - Pan and Sari (2005) ~40 km

reasonably consistent with observations
Collisional Grinding -- Summary

If the Kuiper belt forms in-situ:

• Collisional grinding can remove at least some of the primordial mass
  - Requires most mass to be in small bodies
  - Some dynamical mechanism likely still necessary to match current mass

• Collisional grinding can (reasonably) reproduce the current size distribution
  - Break location close to observed/estimated size
The Dynamical Environment

- The history of the outer Solar System is dynamically complex!

  - Outward migration of Neptune traps Plutinos

- Gomes (2003)
  - 'Hot' Kuiper belt population also pushed out

- Levison and Morbidelli (2003)
  - 'Cold' Kuiper belt population can be pushed out too
  - All of the Kuiper belt potentially formed interior to ~30 AU!
Dynamics -- Continued

- Gomes et al. (2005) – The 'Nice Model'
  - Significant migration of outer planets delayed for \( \sim 700 \) Myr
  - Massive primordial trans-Neptunian disk needs to survive against collisions for \( \sim 700 \) Myr

- Kuiper belt evolution related to scattered disk and Oort cloud evolution
  - Those populations can constrain KB evolution

- New collisional models need to take these dynamical issues into account
Coupling Collisions and Dynamics

- Little work done so far integrating dynamical models with collisional models

- Two examples:
  - Is collisional depletion of the Kuiper Belt consistent with the number of comets in the Oort cloud and scattered disk?
  - Can the trans-Neptunian disk survive for ~700 Myr in the Nice model?
Collisions and the Comet Supply

- Stern and Weissman (2001)
  - If Kuiper Belt was collisionally depleted of its mass, then the Oort cloud should be deficient in comets

- Charnoz and Morbidelli (submitted)
  - What scenario for Kuiper Belt evolution is consistent with estimates of comets in the Oort cloud and scattered disk?
    - Mass depletion through collisional grinding?
    - Mass depletion through dynamical mechanism?
Collisions and Comets -- Cntd.

Charnoz and Morbidelli (submitted)

- Hybrid model
- First: performs orbital integration w/o collisions
- Second: calculates collisional evolution occurring during the integration
- Dynamics affect collisions, but not vice versa

• Tracks evolution of Kuiper Belt, Oort cloud, and scattered disk during giant planet migration
  - Assume constant size distribution throughout disk
  - Migration a la Malhotra (1993,1995)
Collisions and Comets -- Cntd.

- **Case 1**
  - Most mass initially in small bodies
  - Easy to erode away collisionally

Mass and size distribution of KB reproduced!
Collisions and Comets -- Cntd.

- **Case 1**
  - Too few ~1 km comet precursors in Oort cloud and scattered disk (compared to Heisler (1990) and Duncan and Levison (1997) estimates)
Collisions and Comets -- Cntd.

- **Case 2**
  - Most mass initially in large bodies
  - Difficult to erode away collisionally
  - Better match to \( \sim 1 \) km comet precursors in Oort cloud and scattered disk
Collisions and Comets -- Cntd.

- Case 2

Size distribution of KB reproduced!

Mass larger by ~100x

==> Dynamical depletion event is needed!
• Charnoz and Morbidelli (submitted)
  - Supplying enough comet precursors to Oort cloud and scattered disk requires initial population that experiences little collisional erosion
    \[\Rightarrow\] Most of the mass in large bodies
  - Resulting Kuiper belt is massive, and therefore requires a dynamical depletion event to achieve current mass

• Similar simulations should be run for Nice Model!
Collisions and Comets -- Cntd.

- Having enough comets requires that most of the initial TNO mass was in large bodies

- Accretion models predict a population with most of the mass in small bodies
  - Kenyon and Luu (1999) find break at ~100 m diameter

- Need to re-evaluate accretion models
  - Can we form populations with most of the mass in large bodies?
Collisions in the Nice Model

- Nice Model requires ~30 Me trans-Neptunian disk to survive for ~700 Myr
  - Necessary to drive migration of planets to current orbits
  - Necessary to reproduce timing of LHB

- Can a disk from ~15-30 AU survive against collisions for that long?
Collisions in the Nice Model

- Simple collisional model
  - Start w/ 50 Me between 15 and 30 AU, e ~ 0.04
  - Assume Benz and Asphaug (1999) strength law

30 Me can survive!

Final size distribution roughly consistent with Bernstein et al.

O'Brien et al. (DPS 2005)
Collisions in the Nice Model -- Cntd.

• Model is fairly simple
  – Need better estimate/calculation of excitation of disk
  – Need to incorporate accretion
  – Need multi-zone model

• More work necessary to draw solid conclusions

• This issue could be addressed in part with the Charnoz and Morbidelli model
Summary

- Collisions are important for understanding the evolution of the trans-Neptunian population

- Important result from accretion modeling
  - Initial TNO population was much more massive than current population
  - Likely true regardless of specific dynamical model

- Where did the mass go?
  - Collisional grinding can be effective, but probably not sufficient in the in-situ formation case
Collisions and dynamics need to be considered simultaneously.

Most recent model* suggests that the Kuiper belt was dynamically depleted of its mass:
- Significant collisional grinding inconsistent with constraints from scattered disk and Oort cloud comets
- Provides constraints on initial TNO size distribution and strength

*Charnoz and Morbidelli (submitted)
Summary -- Continued

- Goals for future work
  - Continue to integrate dynamical and collisional models, eg. Charnoz and Morbidelli
  - Evaluate collisional constraints on the Nice Model
  - Re-evaluate accretion models for outer Solar System
Trujillo and Brown (2002) found:
- Higher-inclination classical KBOs are bluer
- No trend for plutinos
- No trend with eccentricity
Collisional Surface Processing

- Higher-inclination KBOs are bluer
  - No trend with eccentricity
  - No trend for Plutinos

- Can this be explained collisionally?

- In general, modeling indicates that the trend with inclination can have a collisional origin

Surface Processing -- Continued

- Competing effects
  - Surface irradiation leads to reddening
  - Collisions lead to blueing
  - Higher $i$ means higher impact velocity, more effective resurfacing

- But... (Thebault and Doressoundirama, 2003)
  - Plutinos should show trend with $i$
  - Should be a correlation with $e$ and blueness
  - Neither trend is observed
Surface Processing -- Continued

- Collisions may not be the whole story
- See talk by Peixinho on Friday