Occultation Studies of the Outer Solar System

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Publications


• Han & Gaudi 2005, in preparation

• Gaudi & Han 2005, in preparation
Star Formation 101

- Molecular Cloud
- Cores
- Collapse
- Ignition/Outflow
- Protoplanetary Disk
- Planetary System

Hogerheijde 1998
Planet Formation 101

- Core-accretion Model
- Dust $\rightarrow$ Planetesimals (non G)
- Planetesimals $\rightarrow$ Protoplanets
- Protoplanets $\rightarrow$ Terrestrial Planets
  - Inner Solar System ($<3$AU)
- Protoplanets $\rightarrow$ Gas Giants
  - Outer Solar System ($3$AU-$40$AU)
- Protoplanets $\rightarrow$ Planetoids
  - Distant Solar System ($>40$AU)
The Kuiper Belt – General Properties

- 1st member discovered in 1992 (1992 QB1; Jewitt & Luu 1993)
- ~850 known. Total mass ~1% Earth
- Radial Extent (30-50)AU, peak near 45 AU.

(Trujillo & Brown 2001)
The Kuiper Belt – Dynamical Classes

- Classical
- Resonant
- Scattered
- Extended Scattered??

(Gladman et al. 2001)
The Kuiper Belt – Dynamical Classes

- Classical
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(Elliot et al. 2005) (Gladman et al. 2001)
The Kuiper Belt – Size Distribution

- Power Law
  \[ \Sigma \propto 10^{\alpha m} \]
  \[ \propto r^{-q} \]
  \[ (q = 5\alpha + 1) \]
  - Assumes albedo
- Break
  - age \sim \text{collision time}
  - HST/ACS
  - r \sim 100 \text{ km}

\( \alpha \approx 0.6 \)

(Bernstein et al. 2004)
The Kuiper Belt – Binaries

- At least 5%-10% of KBOs in binaries
- Size ratios ~ unity
- Separations ~ 100 x radius
- Formation mechanisms
  - Weidenschilling (2002)
  - Goldreich et al. (2002)
  - Funato et al. (2003)
  - Astakhov et al. (2005)
The Kuiper Belt – Open Questions

- Extended Scattered Disk?
- Faint-end distribution?
  - Slope?
  - Number?
  - Dynamical classes?
- Albedos/Sizes?
- Close binaries?
- The rest of the solar system?
  - Three orders of magnitude in distance
  - Nine orders of magnitude in volume!
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(Grundy et al. 2005)

canonical ~ 4%
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(Sheppard & Jewitt 2004)
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Limitations of Direct Measurements

- Strong scaling with size and distance

\[ \text{Flux} \propto R^2 d^{-4} \]

- Occultations
  - Bailey (1976)
  - Dyson (1992)
  - Brown & Webster (1997)
  - Roques & Moncuquet (2000)
Principles of Occultations

- Physical Parameters

\[ R, d, \nu \]

- Scales
  - angular size
    \[ \theta = \frac{R}{d} \approx 140 \mu \text{as} \left( \frac{R}{10 \text{km}} \right) \left( \frac{d}{100 \text{AU}} \right)^{-1} \]
  - velocity
    \[ \nu = \nu_\oplus \left( \cos \varphi - \sqrt{\frac{\text{AU}}{d}} \right) \approx 27 \text{km s}^{-1} \text{ at opp.} \]
  - proper motion
    \[ \mu = \frac{\nu}{d} \approx 1'' \text{hr}^{-1} \left( \frac{d}{100 \text{AU}} \right)^{-1} \left( \frac{\nu}{30 \text{ km}} \right) \]
Principles of Occultations

- Observables
  - Duration \( \Delta t \)

\[
\Delta t = 2t_K \sqrt{1 - b^2}
\]

- Crossing Time

\[
t_K = \frac{\theta}{\mu} \approx 0.3s \left( \frac{R}{10\text{km}} \right) \left( \frac{v}{30\text{ km s}^{-1}} \right)^{-1}
\]

Statistical information only
Principles of Occultations

- **Observables**
  - Ingress/Egress time
  - Impact parameter $b$
  - Dimensionless source size

\[
\theta_* \approx 20\mu as \left( \frac{R_*}{R_{\text{Sun}}} \right) \left( \frac{d_*}{250\text{pc}} \right)^{-1}
\]

\[
\rho_* = \frac{\theta_*}{\theta}
\]

\[
\approx 0.1 \left( \frac{R}{10\text{km}} \right)^{-1} \left( \frac{d}{100\text{AU}} \right) \left( \frac{R_*}{R_{\text{Sun}}} \right) \left( \frac{d_*}{250\text{pc}} \right)^{-1}
\]
**Principles of Occultations**

- **Observables**
  - Fringe Spacing
  - Dimensionless Fresnel angle

\[ \theta_F = \sqrt{\frac{\lambda}{d}} \]
\[ \approx 4 \mu \text{as} \left( \frac{\lambda}{545 \text{nm}} \right)^{1/2} \left( \frac{d}{100 \text{AU}} \right)^{-1/2} \]

\[ \rho_F = \frac{\theta_F}{\theta} \]
\[ \approx 0.03 \left( \frac{\lambda}{545 \text{nm}} \right)^{1/2} \left( \frac{d}{100 \text{AU}} \right)^{1/2} \left( \frac{R}{10 \text{km}} \right)^{-1} \]
Principles of Occultations

- Observables
  \[ \Delta t, \rho_*, \rho_F \]

- Parameters
  \[
  d = \frac{\lambda}{2\theta_*^2} \left( \frac{\rho_*}{\rho_F} \right)^2 \\
  R = \frac{\lambda}{2\theta_*} \frac{\rho_*}{\rho_F^2} \\
  v = \frac{\lambda}{2\theta_*} \frac{\rho_*}{\rho_F^2} \frac{1}{t_K}
  \]

\[ \rightarrow R, d, v \]
Parameter Uncertainties

- Light curves
  - 10% errors (V=14)
  - 5 Hz sampling
- Parameters $p_i$
  - N measurements $F_k$

$$c = b^{-1}$$

$$b_{ij} = \sum_{k=1}^{N} \frac{\partial F_k}{\partial p_i} \frac{\partial F_k}{\partial p_j} \frac{1}{\sigma_k^2}$$

- Uncertainties

$$\sigma_i = \sqrt{c_{ii}}$$
Parameter Uncertainties

- Uncertainties
  - Well-constrained
    \( t_K, t_0, b \)
  - Poorly constrained
    \( \rho_*, \rho_K \)
Parameter Uncertainties

- Weak constraints for faint sources
Parameter Uncertainties

- “Next Generation”
- Experiment
  - 3% (V=14)
  - 30 Hz sampling
- Good constraints
Occultations by Binaries

• Detection Rate?
• Binary properties
  – Primary size
  – Size ratio
  – Separation
• Photometric properties
  – Sampling rate
  – Photometric errors
Occultations by Binaries

- Conditional prob.
  - 10 Hz
  - S/N > 10
Occultations by Binaries

- Can detect:
  - 50% of equal-sized binaries with $d/R < \text{few}$
  - 10% of equal-sized binaries with $d/R < 10$
Occutations by Binaries

- Improved precision can dramatically increase rate
  - Especially for small objects

![Graph showing precision rates of 10%, 3%, and 1% for various s/R_i values.](image)
Occultation Surveys

- Challenges
  - Short event duration
    \[ \Delta t \approx 0.6 \left( \frac{R}{10 \text{ km}} \right) \left( \frac{v}{30 \text{ km s}^{-1}} \right)^{-1} \]
  - Low event rate
    \[ \Gamma = \int dr 2\theta \mu \Sigma \]
Occultation Surveys

- Challenges
  - Short event duration
    \[ \Delta t \approx 0.6s \left( \frac{R}{10\text{km}} \right) \left( \frac{v}{30 \text{ km s}^{-1}} \right)^{-1} \]
  - Low event rate
    \[ \Gamma = \int dr 2\theta \mu \Sigma \approx 10^{-5} - 10^{-3} \text{ yr}^{-1} \text{ (R<10km)} \]
  - Monitor >1000 stars
Occultation Surveys

- **Kepler**
  - 100,000 stars
  - μmag precision
  - Long exposure times
  - High ecliptic latitude

![Graph depicting inclination distribution and standard deviation](image-url)
Occultation Surveys

Taiwanese-American Occultation Survey (TAOS)

- Telescopes & Hardware
  - Four 50 cm robotic telescopes
  - f/1.9
  - 2 square degree 2Kx2K cameras
  - Jade Mountain, Taiwan

- Data
  - 2000 stars
  - 5Hz
  - 10% precision
  - Short exposure times
Occulation Surveys

- Shutterless “Zipper” mode
Occultation Surveys

Next Generation Survey
• Requirements
  – Higher cadence
  – Improved photometry
    (reduced sky background)
  – Color information
• Space based
  – Modeled after Kepler
  – Prism
Occultation Surveys

Next Generation Survey

600m at 45 AU  600m at 100 AU
Occultation Surveys

Next Generation
Summary

• Many unanswered questions about the Kuiper belt.
• Outer solar system largely unexplored.
• Reflected light detections limited
• Occultation light curves subject to degeneracies
  – Additional parameters enable parameter measurement
  – High cadence and accurate photometry needed
• Binaries detected via occultations
• Occultation surveys are challenging
  – Short duration
  – Low event rate