The Taiwanese-American Occultation Survey: Results from First Two Years of Data

Zhi-Wei Zhang

TAOS team

IANCU

2008-12-08  TIARA Workshop on Dim KBOs @ NTHU
# The TAOS Collaboration

<table>
<thead>
<tr>
<th>Name</th>
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<tr>
<td>Alcock, C.</td>
<td>Dave, R.</td>
<td>Lissauer, J. J.</td>
<td>Wang, M. J.</td>
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<tr>
<td>Axelrod, T.</td>
<td>de Pater, I.</td>
<td>Marshall, S. L.</td>
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<td>Bianco, F. B.</td>
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<td>Mondal, S.</td>
<td>Wen, C.-Y.</td>
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<td>Byun, Y.-I.</td>
<td>King, S.-K.</td>
<td>Porrata, R.</td>
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<td>Chen, W. P.</td>
<td>Lee, T.</td>
<td>Protopapas, P.</td>
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<td>Coehlo, N. K.</td>
<td>Lehner, M. J.</td>
<td>Rice, J. A.</td>
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<tr>
<td>Cook, K. H.</td>
<td>Lin, H.-C.</td>
<td>Schwamb, M. E.</td>
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</table>

Institute of Astronomy & Astrophysics, Academia Sinica, Taiwan

Institute of Astronomy, National Central University, Taiwan

Harvard-Smithsonian Center for Astrophysics, USA

Department of Astronomy, Yonsei University, South Korea

Department of Physics and Astronomy, University of Pennsylvania, USA

Department of Statistics, University of California, Berkeley, USA

The Institute of Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, USA

Space Science and Astrobiology Division 245-3, NASA Ames Research Center, USA

Kavli Institute for Particle Astrophysics and Cosmology, USA

Division of Geological and Planetary Sciences, California Institute of Technology, USA
INTRODUCTION

Tombaugh (1930) discovered the “dwarf planet” Pluto.
Edgeworth and Kuiper (1950s) conjectured the existence of a belt of small bodies beyond Neptune.
Fernández & Ip (1980s) proposed the origin of the SP comets is from a comet belt beyond Neptune.
Jewitt & Luu (1993) first discovered a classical KBO (1992 QB\(_1\), \(d \approx 250\) \(km\)) beyond Neptune.
INTRODUCTION

Outer Solar System

Plot prepared by the Minor Planet Center (2008 Sept 25).
**Introduction**

Dynamical classification: CKBOs, Plutino (Resonant KBOs), Scattered KBOs, etc.
**Introduction**

Dynamical classification: CKBOs, Plutino (Resonant KBOs), Scattered KBOs, etc.

What fraction of the population is in each classification? How can these objects come into resonance? What happened at “50 AU”? 

Scientific Goal

Conduct a census of small KBOs (∼ 1 km)

The observation ⇒ 0.01 – 0.1 $M_\oplus$
The minimum mass solar nebula ⇒ ∼ 10 $M_\oplus$
The simulation result ⇒ ∼ 10 $M_\oplus$

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**Scientific Goal**

conduct a census of small KBOs $\Rightarrow$ size distribution of KBOs

![Graph showing size distribution of KBOs](image)

*Trujillo et al.* (2001)
**Scientific Goal**

conduct a census of small KBOs \implies size distribution of KBOs

(cumulative luminosity function)

Trujillo et al. (2001)
Bernstein et al. (2004)
Fraser et al. (2008)
**Scientific Goal**

conduct a census of small KBOs  \(\Rightarrow\) size distribution of KBOs

(cumulative luminosity function)

Trujillo et al. (2001)

Bernstein et al. (2004)

Fraser et al. (2008)
Census of KBOs

Observational Strategy: chance stellar occultations by comet-size KBOs

<table>
<thead>
<tr>
<th>KBO</th>
</tr>
</thead>
<tbody>
<tr>
<td>heliocentric distance</td>
</tr>
<tr>
<td>angular diameter (for 6 km)</td>
</tr>
<tr>
<td>speed at opposition</td>
</tr>
<tr>
<td>occultation duration at opposition</td>
</tr>
</tbody>
</table>
To increase the detection rate & To decrease false positive

Wide-field telescopes

An array of 4 telescopes, each with the fast (f/1.9) optics equipped with the 2k x 2k CCD camera (2.9 sq degrees), to monitor a couple of thousand stars simultaneously.

To detect the events by the KBO with the cometary size

Subsecond sampling rate scheme (zipper mode)

The CCD camera reads out few rows sequentially at a time after an integration while the shutter remains open.
INSTRUMENTATION

Layout of the TAOS array of 4 telescopes at Lulin site
DATA ACQUISITION

a part of zipper-mode image
DATA ACQUISITION

a part of zipper-mode image
archieving 0.2 s sampling time and yet imaging stars on CCD zipper mode: a row block
DATA ACQUISITION AND IMAGE PROCESS

archiving 0.2 s sampling time and yet imaging stars on CCD
zipper mode: a row block

remove streaks: column mode
custom aperture photometry
Illustration of *Rank Statistics*: Case A.

<table>
<thead>
<tr>
<th>flux</th>
<th>A</th>
<th>1.2</th>
<th>0.9</th>
<th>0.8</th>
<th>1.1</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>0.9</td>
<td>1.3</td>
<td>1.1</td>
<td>0.7</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>1.0</td>
<td>1.2</td>
<td>0.9</td>
<td>1.1</td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>
Illustration of *Rank Statistics*: Case A.

<table>
<thead>
<tr>
<th>rank</th>
<th>A</th>
<th>B</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>flux</td>
<td>1.2</td>
<td>0.9</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>1.1</td>
<td>0.7</td>
<td>0.7</td>
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</tbody>
</table>
Event Detection

Illustration of Rank Statistics: Case A.

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<tr>
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<td>0.9</td>
<td>1.1</td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ranking order</th>
<th>A</th>
<th>5</th>
<th>2</th>
<th>1</th>
<th>4</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Π</td>
<td>60</td>
<td>50</td>
<td>8</td>
<td>12</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>
Event Detection

Illustration of Rank Statistics: Case B.

<table>
<thead>
<tr>
<th>flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>D</td>
</tr>
</tbody>
</table>
Event Detection

Illustration of *Rank Statistics*: Case B.

<table>
<thead>
<tr>
<th>flux</th>
<th>A</th>
<th>B</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>0.9</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>0.9</td>
<td>1.3</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>1.0</td>
<td>1.2</td>
<td>0.5</td>
<td>1.1</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>ranking order</th>
<th>A</th>
<th>B</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>4</td>
<td>3</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>3</td>
<td>32</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>2</td>
<td>18</td>
</tr>
</tbody>
</table>
Illustration of Rank Statistics: Case B.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux</td>
<td>1.2</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Rank</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Product of Rank</td>
<td>60</td>
<td>50</td>
<td>18</td>
</tr>
</tbody>
</table>

Ordering:
- A 1.2 0.9
- B 0.9 1.3
- D 1.0 1.2

The Taiwanese-American Occultation Survey: – p. 15/2
Event Detection

Rank statistics

To quantify if a possible occultation event is in the light curves, we use the non-parametric statistic of rank order

\[ N \text{ MEASUREMENT OF LIGHT CURVES} \]

\[
\text{sort by time} \quad (f_1, f_2, f_3, \cdots, f_N) \quad \rightarrow \quad (f_{19}, f_5, f_{58}, \cdots, f_3) \\
\text{sort by flux} \quad \| \quad (r_1, r_2, r_3, \cdots, r_N) \quad \leftarrow \quad \left(1, 2, 3, \cdots, N\right)
\]

\[
R_i = -\log \left( \prod_{k=1}^{N_{\text{scope}}} \frac{r_k}{N} \right) = \sum_{k=1}^{N_{\text{scope}}} \left( -\log \frac{r_k}{N} \right), \text{ where } N_{\text{scope}} \text{ is number of telescopes.}
\]

\[ r : \text{uniform distribution} \rightarrow \rightarrow \rightarrow R : \text{gamma distribution} \]

\[
P(\alpha, R) = \frac{1}{\Gamma(\alpha)} R^{\alpha-1} e^{-R}
\]

when \( N \rightarrow \infty \)
Event Detection

Rank statistics: $f_i \xrightarrow{\text{rank}} r_i$ and then $\prod_{k}^{ntel} r_i^k$ over number of telescopes
Event Detection

Rank statistics: \( f_i \xrightarrow{\text{rank}} r_i \) and then \( \prod_{k} r_i^k \) over number of telescopes.
**Event Detection**

Rank statistics: \( f_i \xrightarrow{\text{rank}} r_i \) and then \( \prod_k n_{tel} r_i^k \) over number of telescopes.
Event Detection

Rank statistics: $f_i \xrightarrow{\text{rank}} r_i$ and then $\prod_k r_i^k$ over number of telescopes.
Event Detection

Rank statistics: $f_i \xrightarrow{\text{rank}} r_i$ and then $\prod_{k}^{n_{tel}} r_k^i$ over number of telescopes

The Taiwanese-American Occultation Survey: – p. 17/23

$P(Z > z) = 3.7 \times 10^{-10}$

RANKS = (8, 1, 1)
**RESULTS**

**Summary of Lightcurve Sets**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start Date</td>
<td>2005 February 7</td>
</tr>
<tr>
<td>End Date</td>
<td>2006 December 31</td>
</tr>
<tr>
<td>Total Volume</td>
<td>15 TB</td>
</tr>
<tr>
<td>Number of Data Runs</td>
<td>156</td>
</tr>
<tr>
<td>Number of Lightcurve Sets</td>
<td>110,895</td>
</tr>
<tr>
<td>Total Exposure</td>
<td>153,209 star-hours</td>
</tr>
<tr>
<td>Number of Photometric Measurements</td>
<td>$2.367 \times 10^9 \times 3$</td>
</tr>
</tbody>
</table>

1. lightcurve sets only containing three-telescope data
2. excluding lightcurve sets with measurements less than 10,000
3. 30 data runs with a 4 Hz sampling rate; others with 5 Hz
threshold \[ c = 10^{-10} \]
false positive events \[ 2.36 \times 10^9 \times c \sim 0.236 \]
RESULTS

\[ c = 10^{-10} \]

false positive events \[ 2.36 \times 10^9 \times c \sim 0.236 \]

\[ \Rightarrow \text{No statistically significant events found from this data set by using this analysis!} \]
RESULTS

threshold \[ c = 10^{-10} \]
false positive events \[ 2.36 \times 10^9 \times c \sim 0.236 \]

⇒ *No statistically significant events found from this data set by using this analysis!*

Q. What can we do?!
RESULTS

threshold \( c = 10^{-10} \)
false positive events \( 2.36 \times 10^9 \times c \sim 0.236 \)

\[ \Rightarrow \text{No statistically significant events found from this data set by using this analysis!} \]

Q. What can we do?!
A. Set an upper limit on the size distribution.
To understand the detection sensitivity of our data and analysis to different event parameters such as \([\text{size, relative velocity, impact parameter,} \ldots]\), we do an efficiency test.
EFFICIENCY TEST

To understand the detection sensitivity of our data and analysis to different event parameters such as \( \text{size, relative velocity, impact parameter, ...} \), we do an efficiency test.

ALL of lightcurve sets
To understand the detection sensitivity of our data and analysis to different event parameters such as \([\text{size, relative velocity, impact parameter, ...}]\), we do an efficiency test directly related to the signal-to-nose ratio of lightcurves sets.
**Efficiency Test**

To understand the detection sensitivity of our data and analysis to different event parameters such as [size, relative velocity, impact parameter, ...], we do an efficiency test.

1° implant an occultation event into a lightcurve set with a certain size of KBO

2° sizes of KBO in km: \( D = [0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 2, 3, 6, 10, 30] \)

3° do the analysis again

4° count how many lightcurve sets with recovered events and then

5° sum those usable lightcurve sets up to derive the effective solid angle

\[
\Omega_e(D) = \sum_j E_j v_{rel_j} h_j(D),
\]

where \( E \) is observing length of lightcurve, \( v_{rel} \) is relative velocity, and \( h(D) \) is cross section of KBO.
(a) choose a power-law size distribution $D^{-q}$ for small KBOs.

(b) assume our result obeys a Possion dist., the upper bound of $N_{\text{exp}}$ for no detections at 95% confidence interval is about 3.
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(b) assume our result obeys a Poisson dist., the upper bound of $N_{\text{exp}}$ for no detections at 95% confidence interval is about 3.
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(b) assume our result obeys a Possion dist., the upper bound of $N_{\text{exp}}$ for no detections at 95% confidence interval is about 3.

(c) integrate the size distribution over the size from 28 to 5 km

$$3 = N_{\text{exp}} = \int_{0.5}^{28} c \left[ \frac{D^{-q}}{D_{28}} \right] \Omega_e(D) dD$$
(a) choose a power-law size distribution $D^{-q}$ for small KBOs.

(b) assume our result obeys a Possion dist., the upper bound of $N_{\exp}$ for no detections at 95 % confidence interval is about 3.

$q = 4.6$
THE TAOS COLLABORATION

Institute of Astronomy & Astrophysics, Academia Sinica, Taiwan
Institute of Astronomy, National Central University, Taiwan
Harvard-Smithsonian Center for Astrophysics, USA
Department of Astronomy, Yonsei University, South Korea
Department of Physics and Astronomy, University of Pennsylvania, USA
Department of Statistics, University of California, Berkeley, USA
The Institute of Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, USA
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