

The Taiwan-America Occultation Survey (TAOS) Project --- Current Status

Wen-Ping Chen (陳文屏)
(National Central University, Taiwan)
on behalf of the TAOS collaboration

Target Earth: Search for Earth-intercepting
asteroids and comets



2005.06.03 @ CAST

Outlines

- A Quick Overview of the Project
 - Concept and Experimental design
- Current Status

What do we get to hear from the TAOS talks in the sessions



Collaborators

- **USA**

C. Alcock, Federica Bianco (*CfA*)

Rahul Dave, Joe Giammarco, Matt Lehner, Megan Schwamb
(*U. Penn*)

K. Cook, Rodin Porrata (*LLNL*)

S. Marshall (*SLAC*)

I. de Pater, J. Rice (*UC/Berkeley*)

J. Lissauer (*NASA/Ames*)

- **Taiwan**

T. Lee, C.Y. Wen, S.K. King, A. Wang, S.Y. Wang (*ASIAA*)

W.P. Chen, W. Ip, Y.H. Chang, D. Kinoshita, H. C. Lin,
Soumen Mondal, Z. W. Zhang (*NCU*)

- **Australia** T. Axelrod (*U Arizona*)

- **Korea** Y. I. Byun (*Yonsei U*)

Solar System Formation in a Nutshell

The Sun and planets were formed out of
an interstellar molecular cloud.

Cloud collapsed

central $T \uparrow$ nuclear fusion

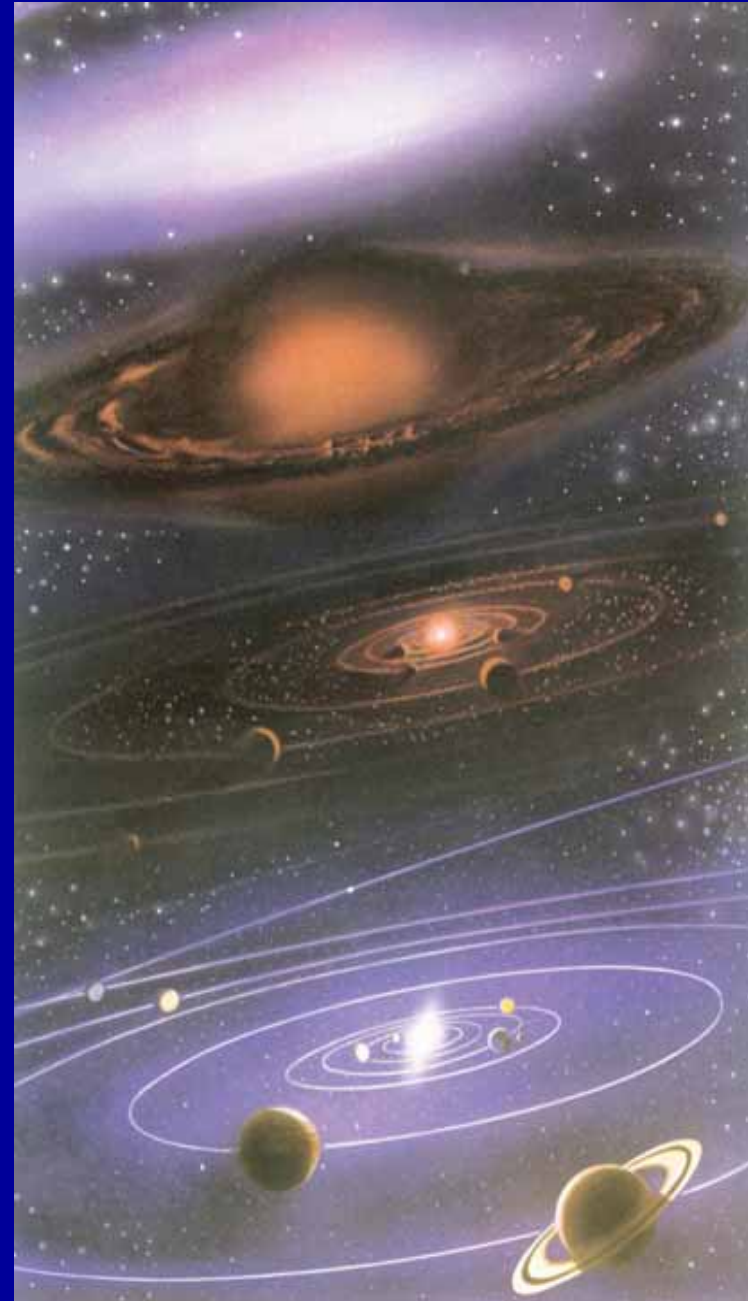
→ **Sun**

dust coagulated in circumstellar disk

→ **planetesimals** (asteroids)

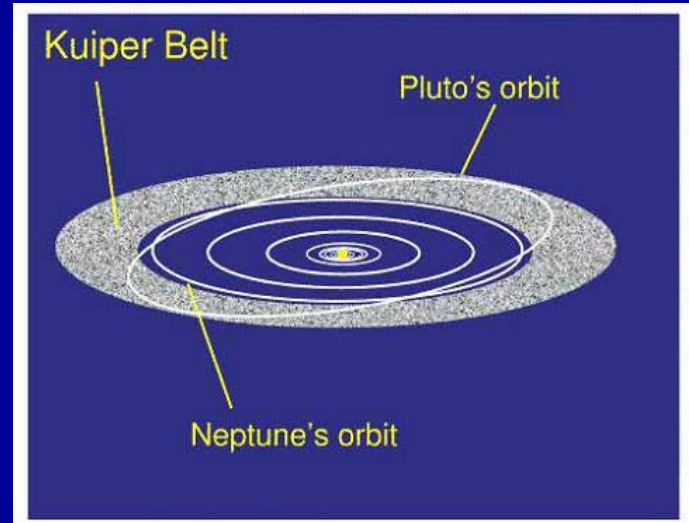
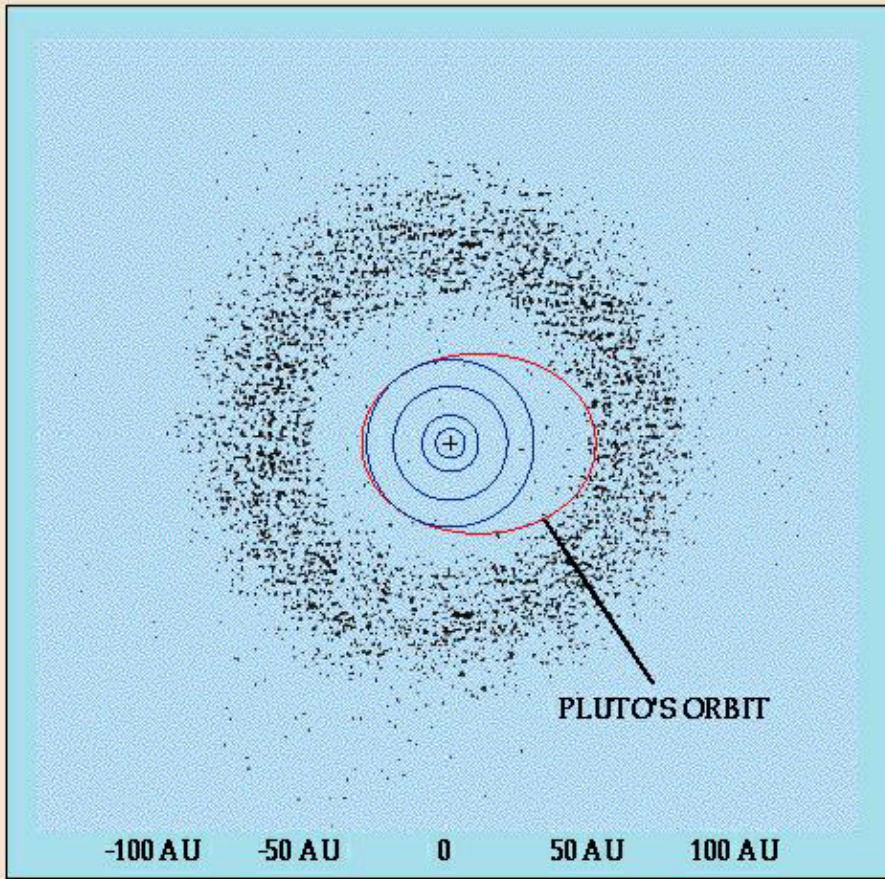


Heavy bombardments
shaped the planets and
satellites ...

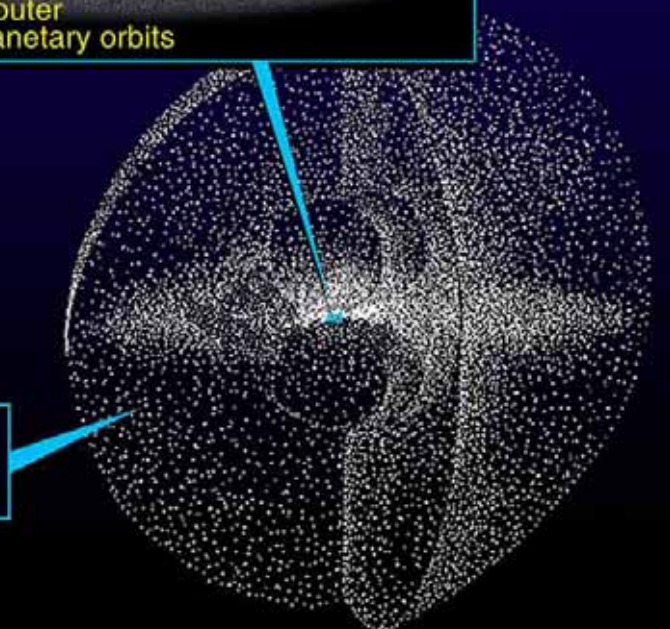


The surplus material and planetesimals become the Kuiper disk or Kuiper belt.

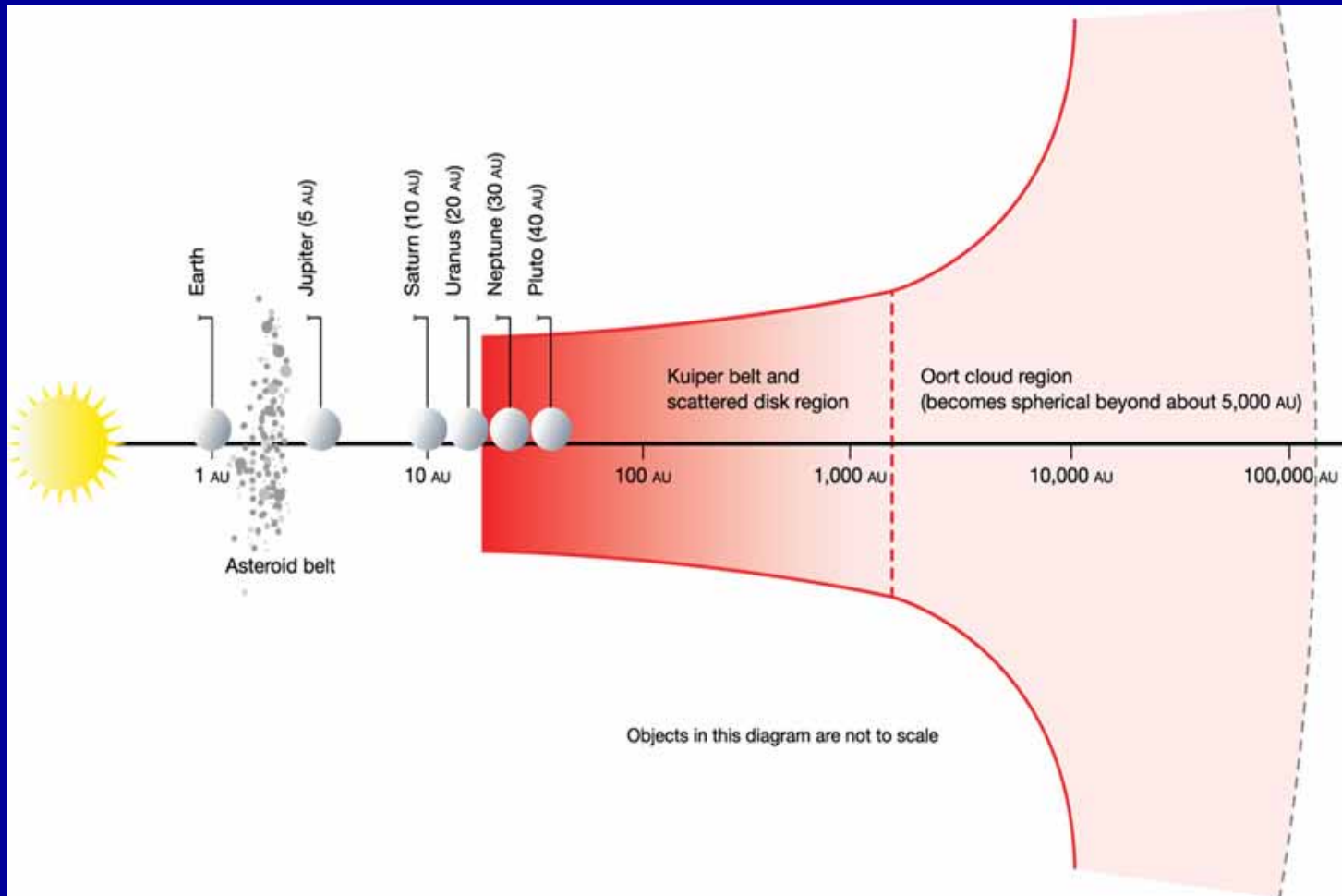
THE OUTER PLANETS AND THE KUIPER DISK



**The Oort Cloud
(comprising many
billions of comets)**



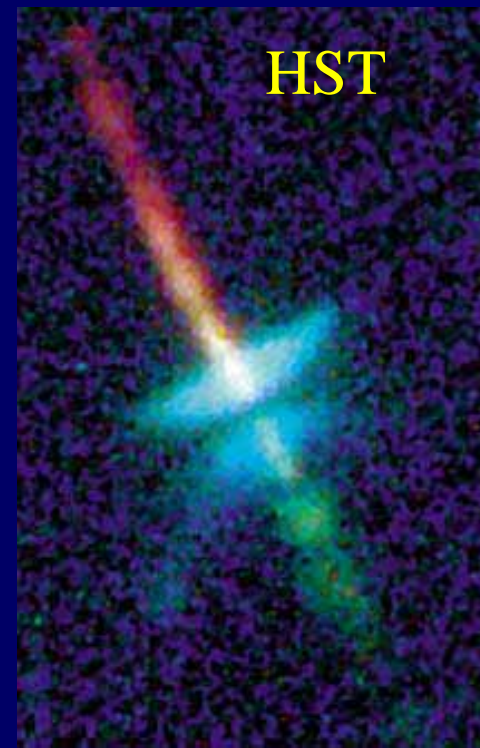
*Oort Cloud cutaway
drawing adapted from
Donald K. Yeoman's
illustration (NASA, JPL)*



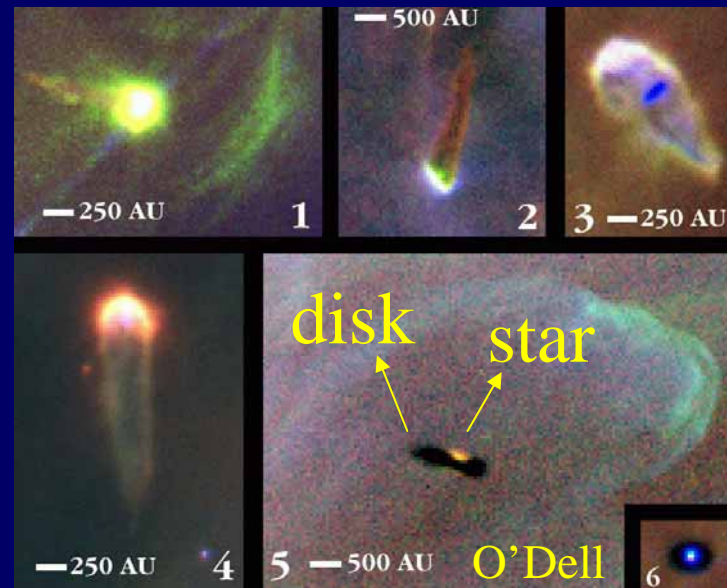
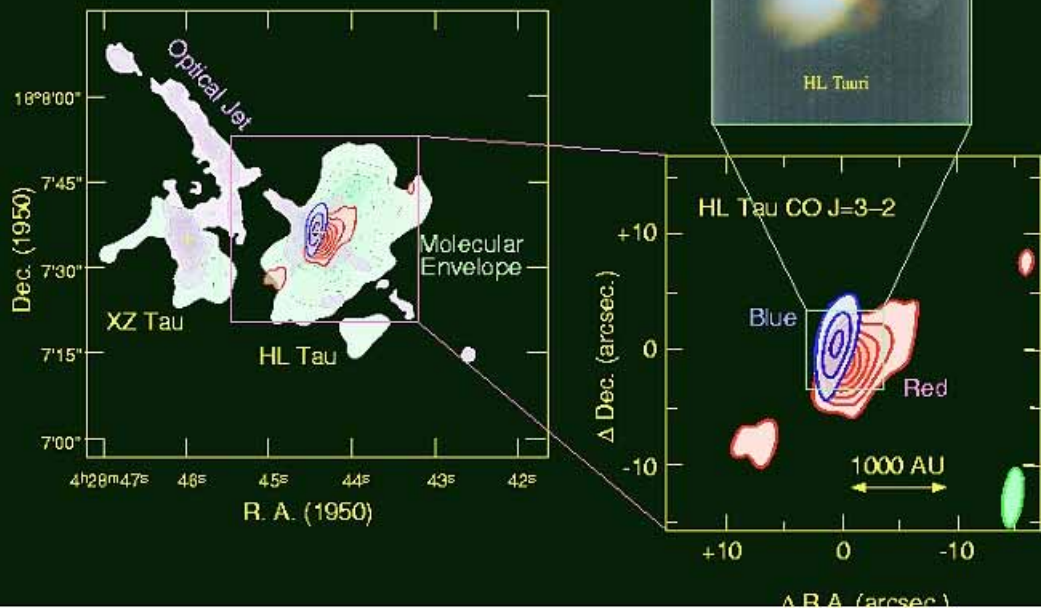
The Kuiper belt is the remnant planetary disk extending beyond Neptune to perhaps > 1,000 AU.

Stern (2003)

Circumstellar disks are ubiquitous among sunlike young stars ...

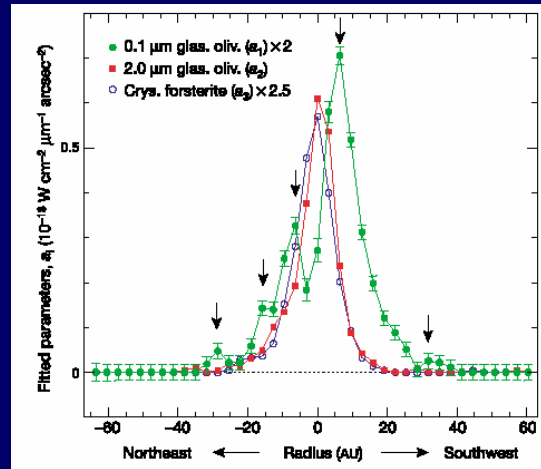
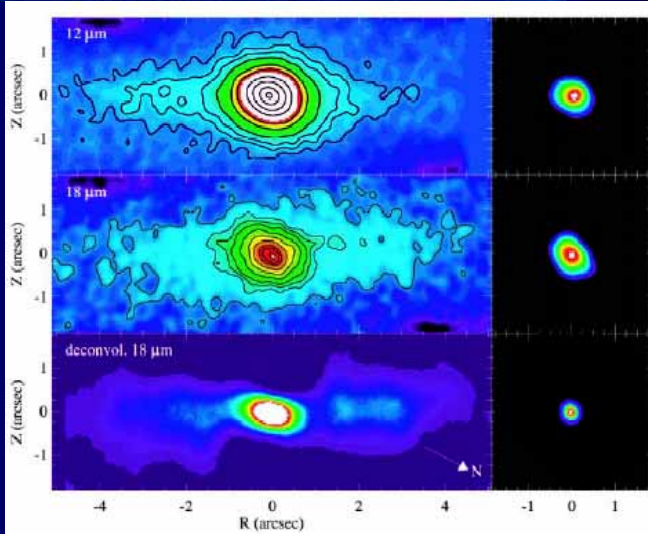
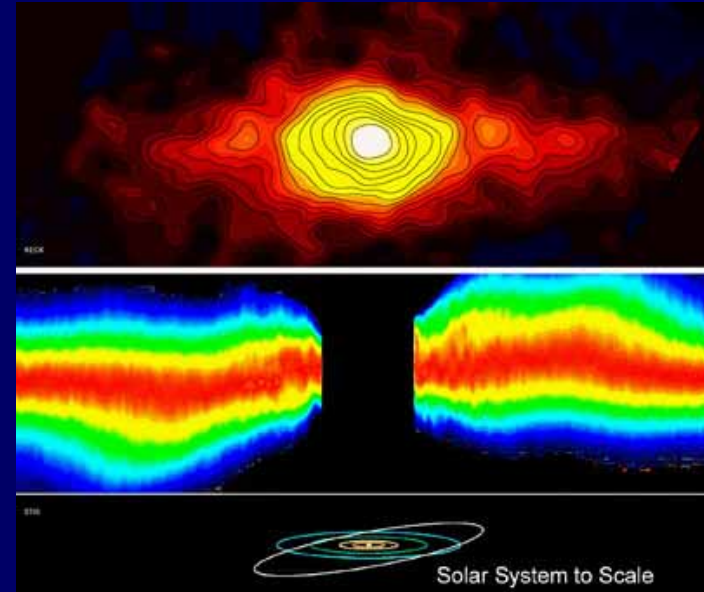
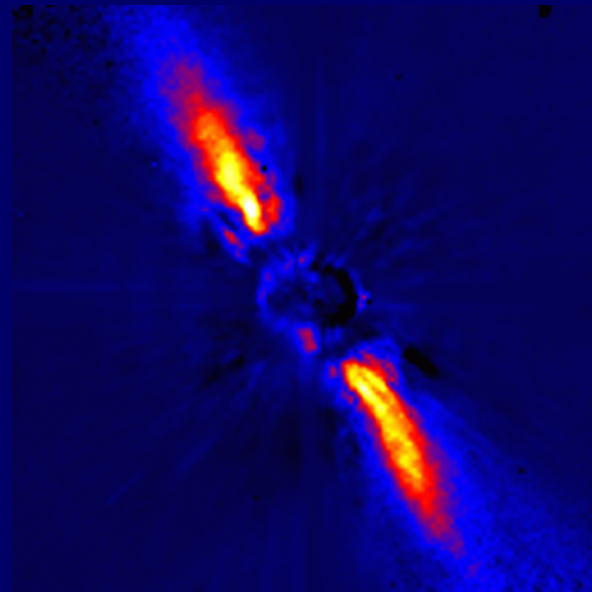
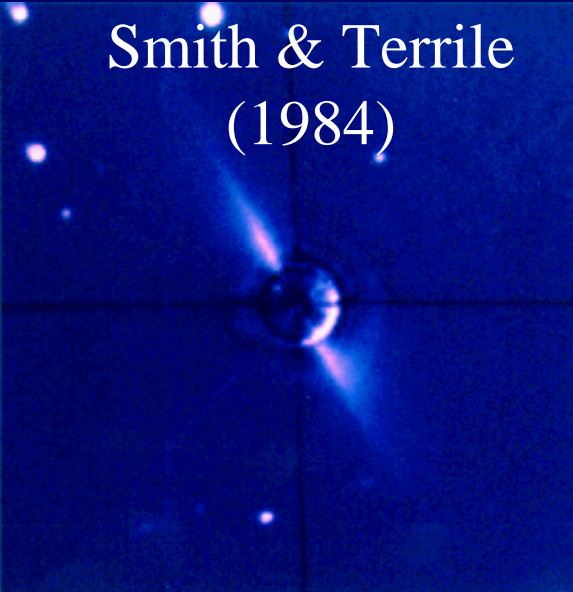


SMA

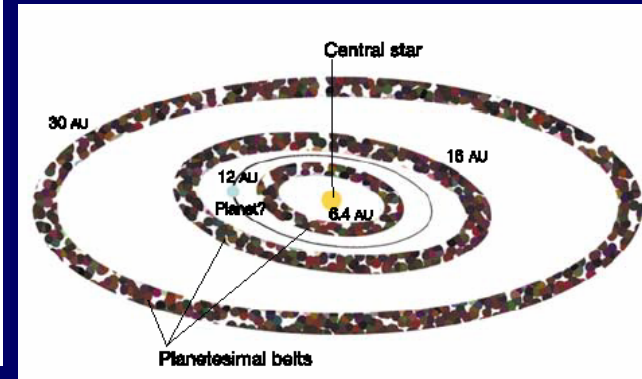


Debris planetary disk around Beta Pictoris

Smith & Terrile
(1984)



Schultz & Heap



11.7 & 17.9 micron images
(Weinberger et al 2003)

Dust emission has peaks at 6, 16,
and 30 AU (Okamoto et al. 2004)

Kuiper-belt population in our Solar System is known to exist.

Distant EKOS --- *The Kuiper Belt E-Newsletter*

(<http://www.boulder.swri.edu/ekonews/>)

As of 2005/06

Current number of TNOs: 886 (and Pluto & Charon, and 12 other TNO binary companions)

Current number of Centaurs/SDOs: 151

Current number of Neptune Trojans: 2

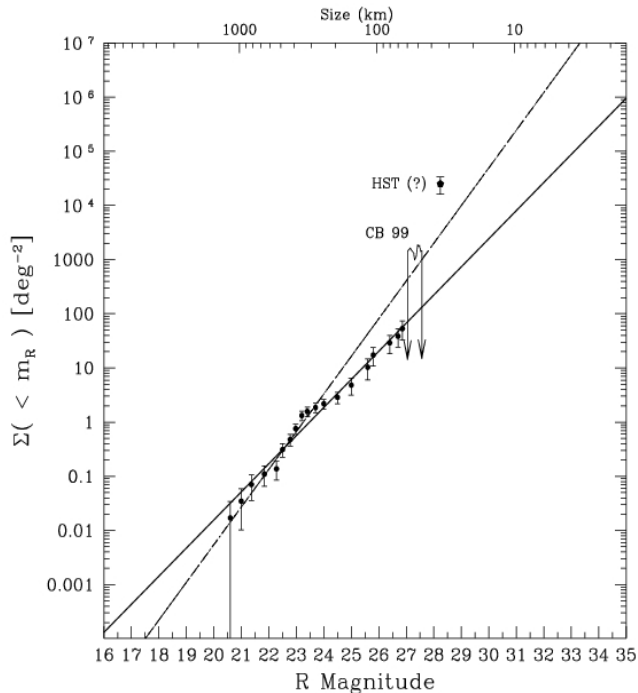
Out of a total of 1039 objects:

500 have measurements from only one opposition

410 of those have had no measurements for more than a year

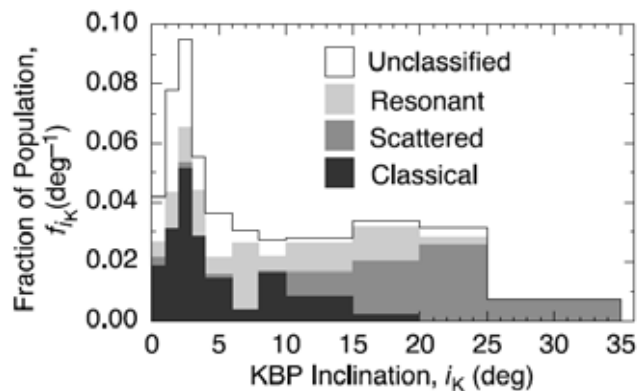
203 of those have arcs shorter than 10 days

Kuiper-belt objects (KBOs) = Edgeworth-Kuiper Objects (EKOs)
= Transneptunian Objects (TNOs)



Statistical studies now become possible

A deficit at small-size end?



Distinctly different populations!

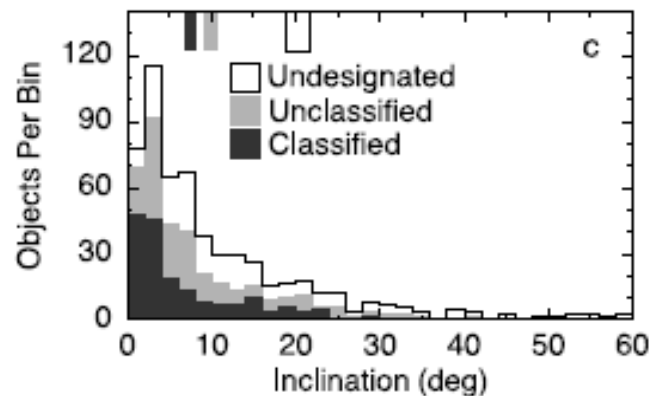
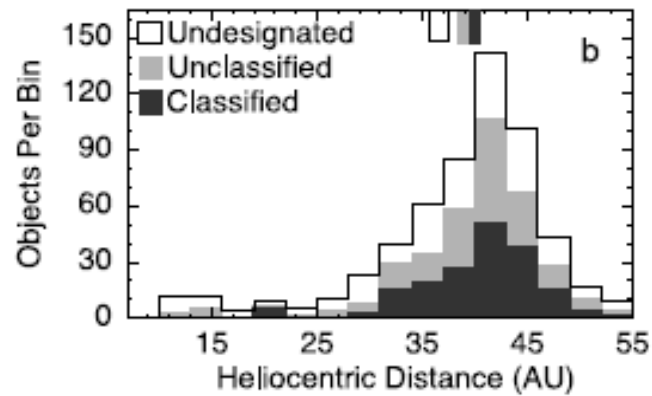
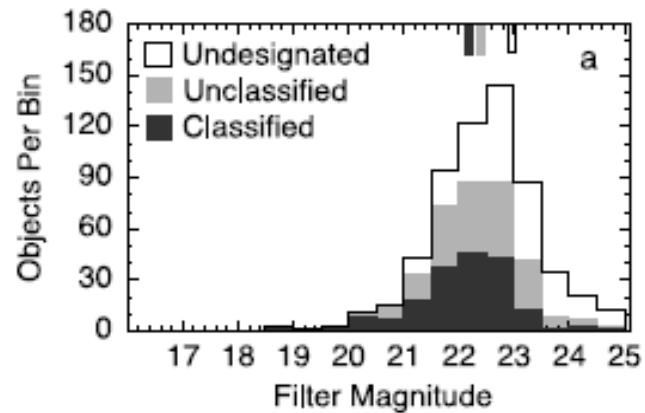
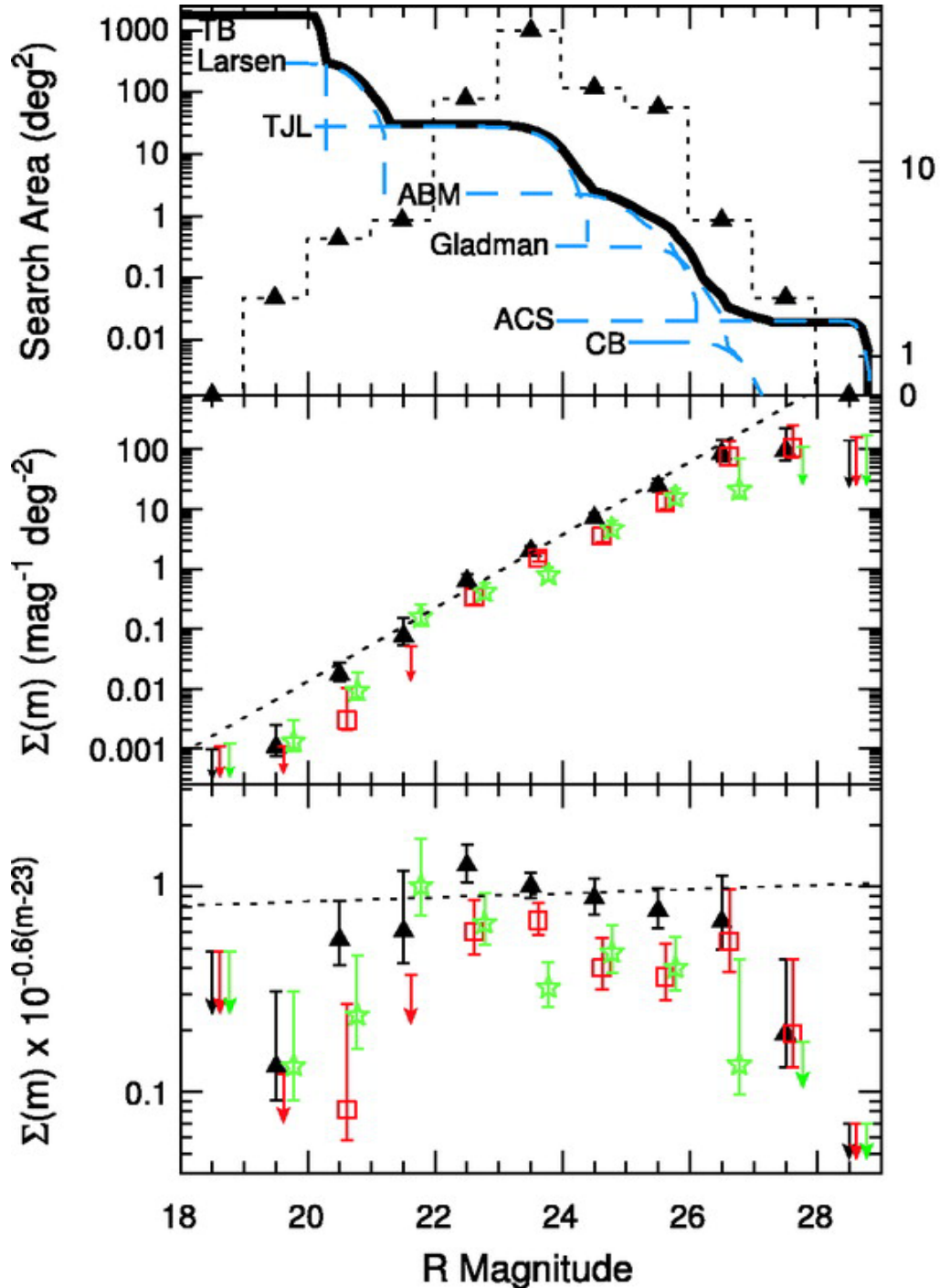


FIG. 17.—The unbiased KBP inclination distribution as a function of KBO classification. The fraction of objects in the sample per degree of inclination is the same as Fig. 16, with each bin shaded to reflect the proportion of objects by classification. Unclassified objects are represented by open areas, Resonant objects are light gray, Scattered (Near and Extended) objects are dark gray, and Classical objects are black. The low-inclination “core” is primarily composed of Classical objects, while the higher inclination “halo” is primarily Scattered objects. Along the KBP inclination axis, the boundary between Classical and Scattered objects is not distinct.

Elliot et al. 2005





HST/ACS with 22 ks per pointing found 3 KBOs, with the faintest of 28.3 mag, corresponding to a size of 25 km!

Deficit in both large and small bodies

Classical KB and Excited KB are different

CKBOs mostly 100 km bodies with a second peak <10 km

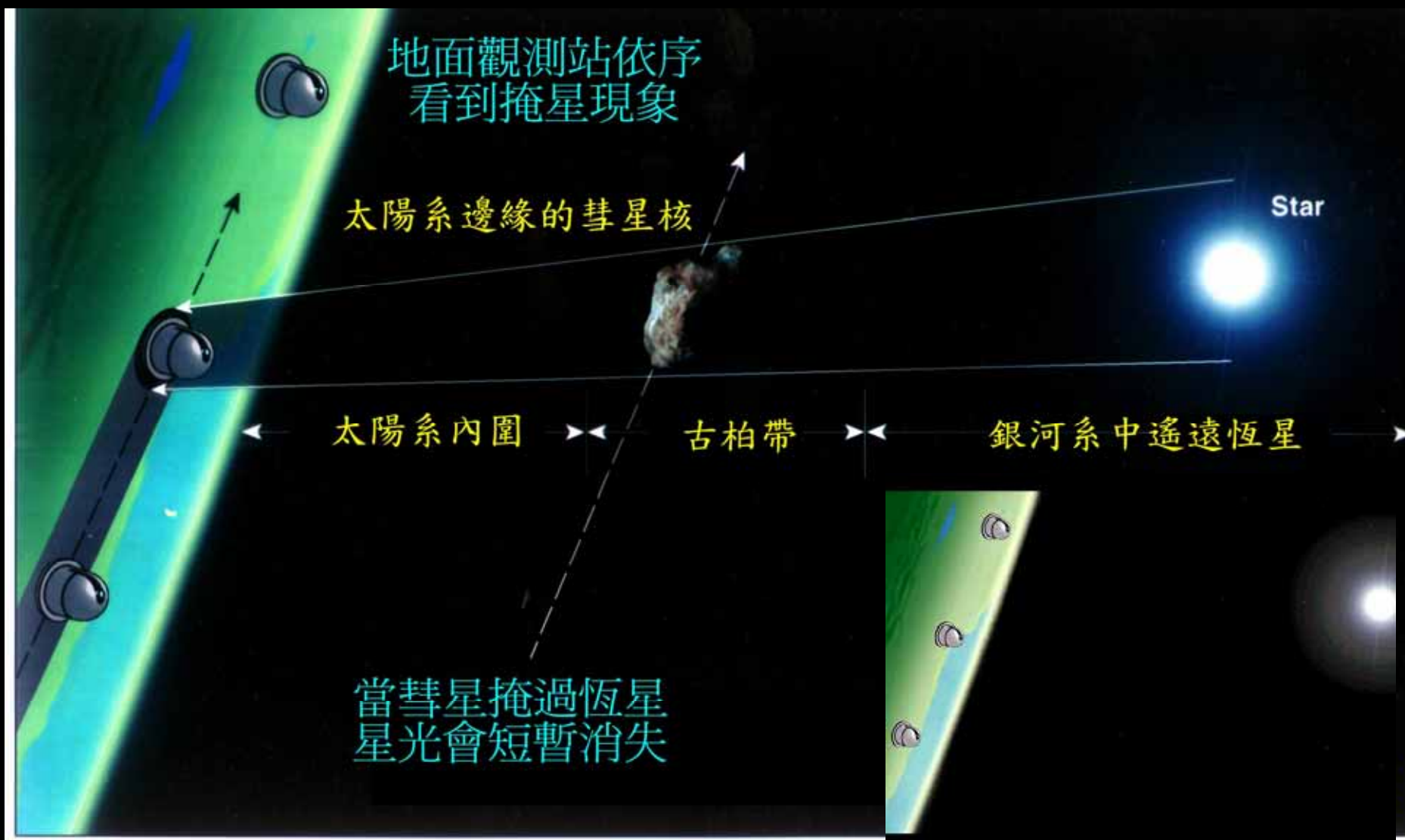
Largest EKBOs=Pluto

Burnstein et al. (2004)

- ✓ KBOs are building blocks of planets/satellites, so bear much information of formation and evolution history of the Solar System.
 - ✓ But they can be studied only when come near the Sun/Earth and display cometary behavior.
 - ✓ Otherwise they are extremely faint $B \propto [\text{size}]^2(1/d)^2$
 - ✓ Only the largest ($>$ a few tens km) can be seen by reflected sunlight
 - ✓ Smaller ones (\sim km), though likely much numerous on theoretical grounds (e.g., Kenyon & Bromley 2004), cannot be seen even with the largest telescopes.
- We just begin to learn about their spatial distribution, sizes, composition. But we really do not even know **their total number**, especially the small ones (collisional fossils?)

Hence the TAOS project --- to 'see' them by blocking starlight

TAOS will detect KBOs by stellar occultation

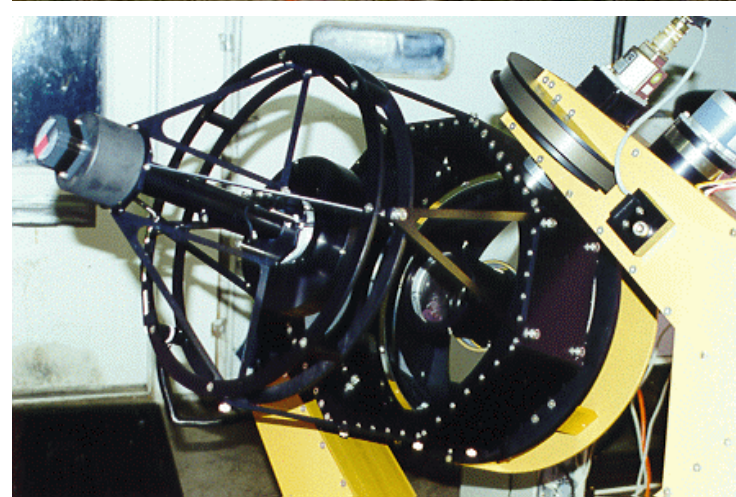


All along, TAOS has been a highly challenging project!!

An uphill battle 2000/04



Enclosure installation



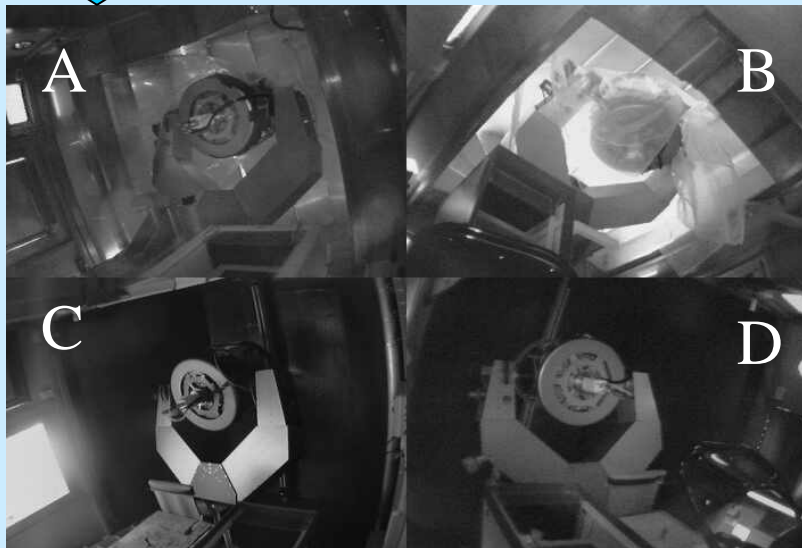
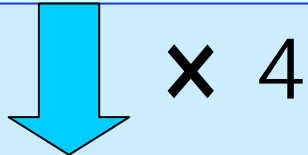
TAOS telescope: $D=0.5$ m; $f/1.9$

Hardware

- ❑ 50 cm f/1.9 Cassegrain by Torus
- ❑ SI800 camera (2K sq EEV) by Spectral Instruments
- ❑ Self-designed, customer-made enclosure



by SK King (15 Oct. 2004)



Real-time webcam images of the 4 TAOS telescopes (by SK King, 26 Oct. 2004)



鹿林天文台

Elevated to 2862m; above inversion layer



... seen from Yusan (Jade Mt)



LELIS



SLT



窄波段巡天計畫

中美掩星計畫
3號望遠鏡

超輕型望遠鏡

中美掩星計畫
4號望遠鏡

控制中心
1m望遠鏡

中美掩星計畫
1, 2號望遠鏡

LOT

TAOS

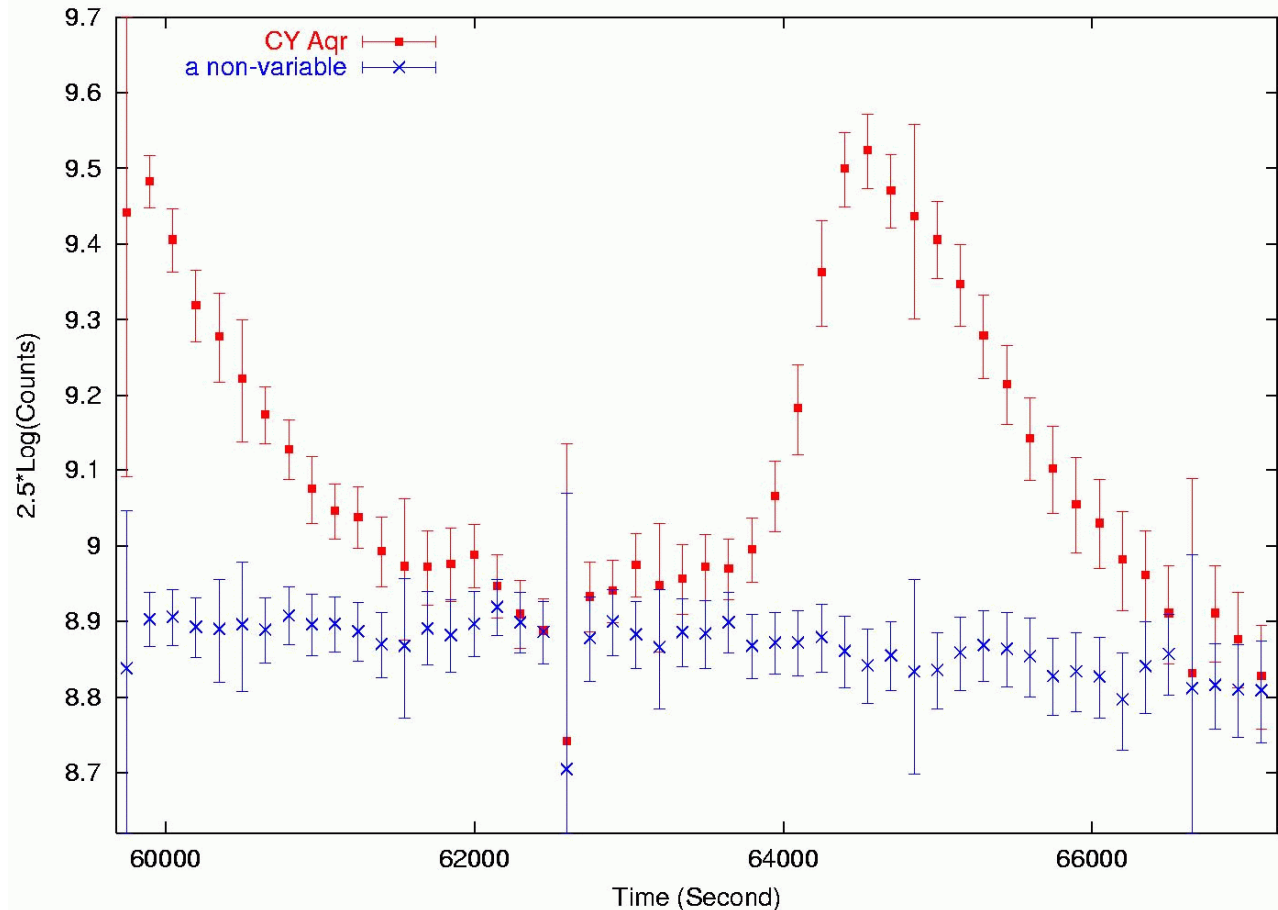


LULIN OBSERVATORY

TAOS Telescopes



TEST DRIVE 1



CY Aqr, a known Delta-Scuti star with $P \sim 88$ min, was observed by TAOS on 2003 September 16 with 0.3 s sampling, here binned to 150 s for illustration.

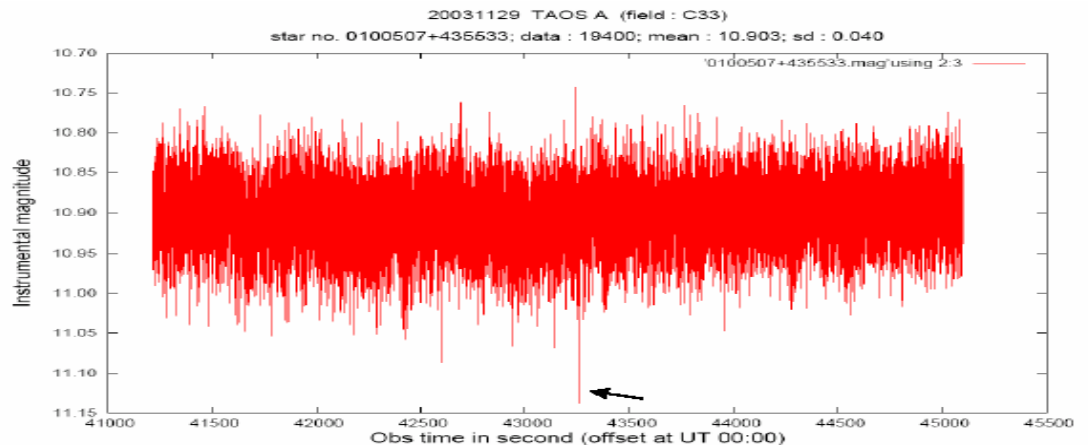
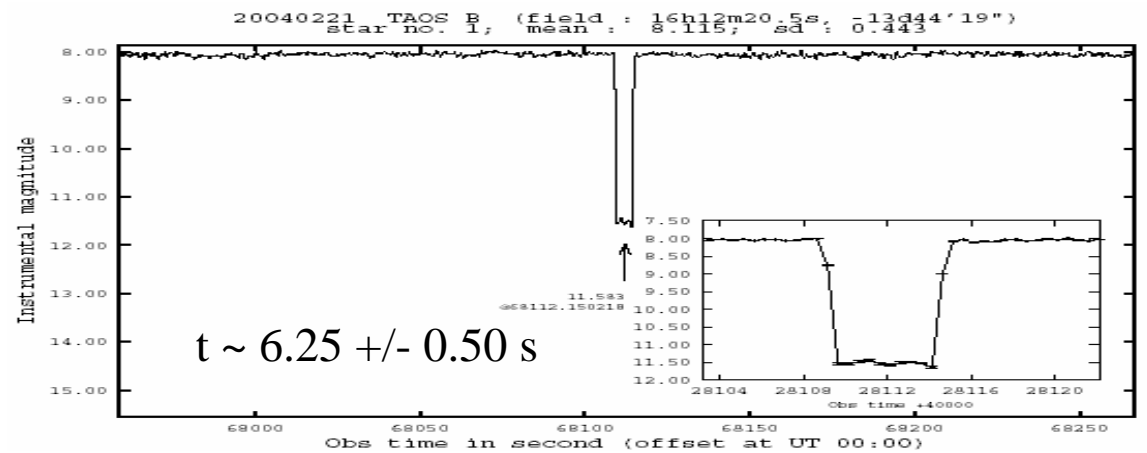
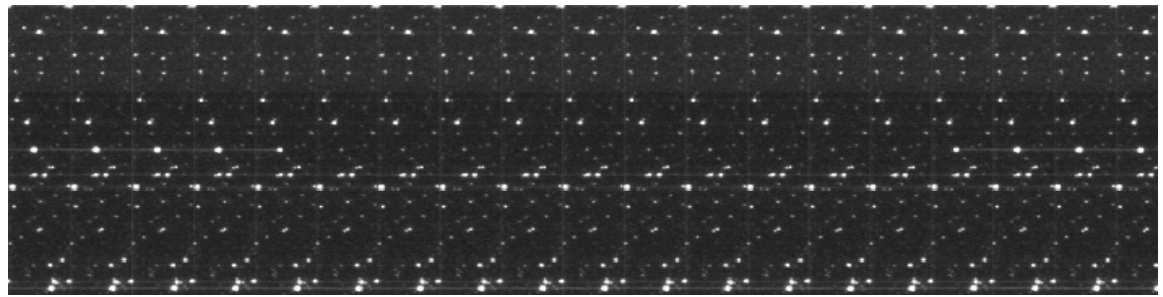
→ **time-domain astrophysics**

TEST DRIVE 2

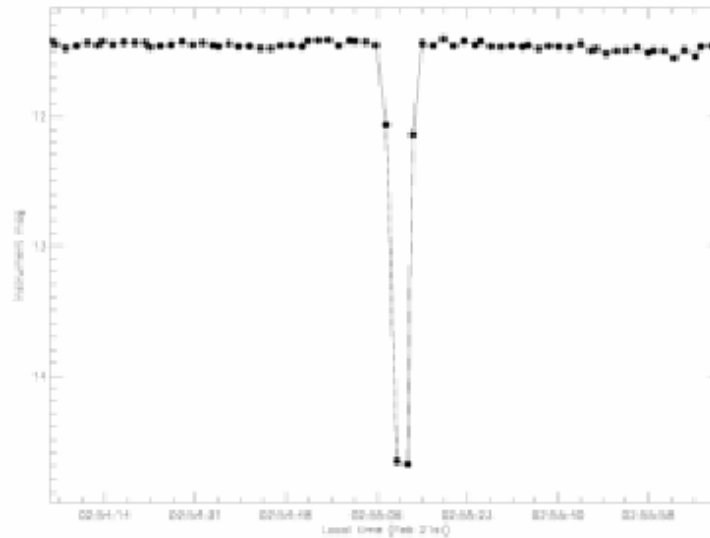
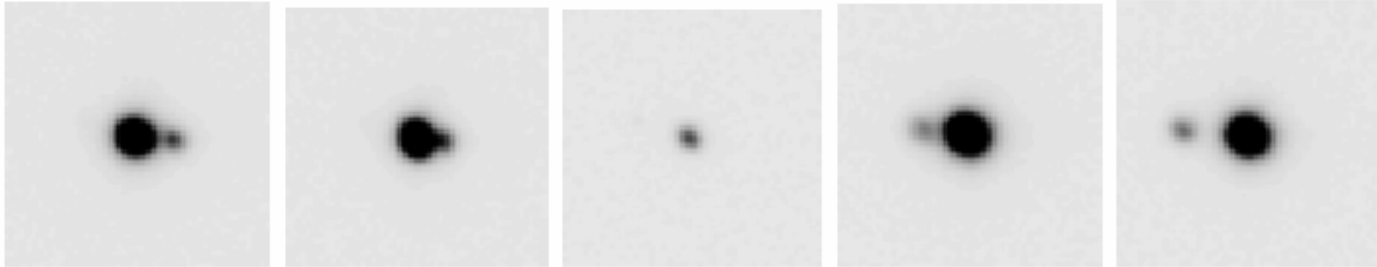
2004 February 21
TAOS detected the
occultation event
of HIP 079407,
 $m_V=8.8$ mag) by
(51) Nemausa
($m_V=11.9$)

Prediction by Isao Sato
(左藤勲)

D~150 km



The 1 m telescope at Lulin also detected the same event with traditional CCD imaging.



$t_{\text{exp}} = 1 \text{ s}$
 $t_{\text{ro}} < 2 \text{ s}$

By A. Chen

TEST DRIVE 3

2004 June 05 TAOS detected the occultation of HIP 050525 ($m_V \sim 8.46$ mag) by **(1723) Klemola** ($m_V \sim 15.7$ mag; $D \sim 31$ km) with two telescopes

TAOS/A

TAOS/B

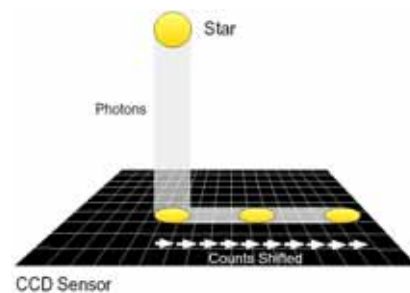
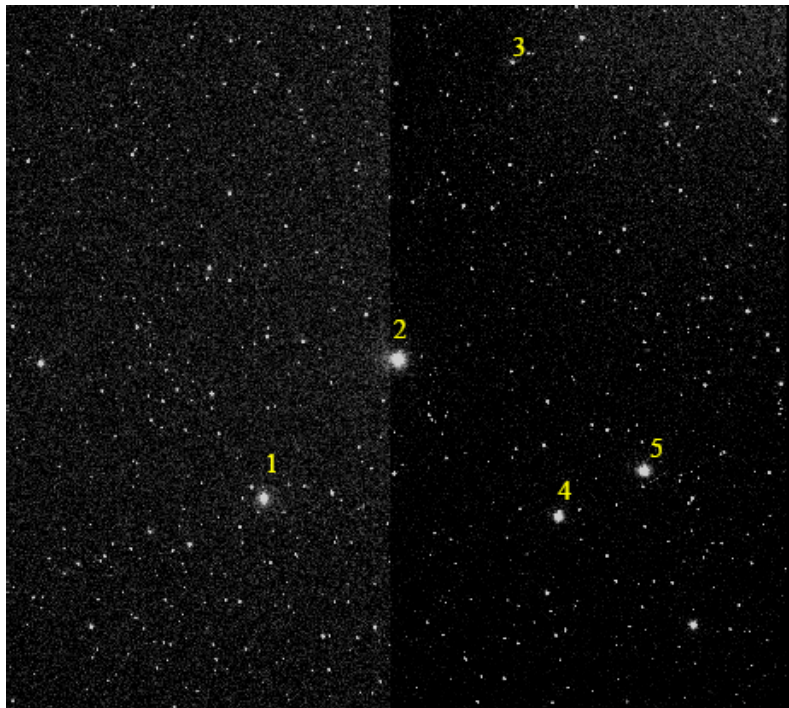
Enclosure opened by a resident assistant and observations carried out remotely from Taipei



Data Acquisition

Typical CCD imaging

Every star, together with surrounding skies, get exposure at the same time

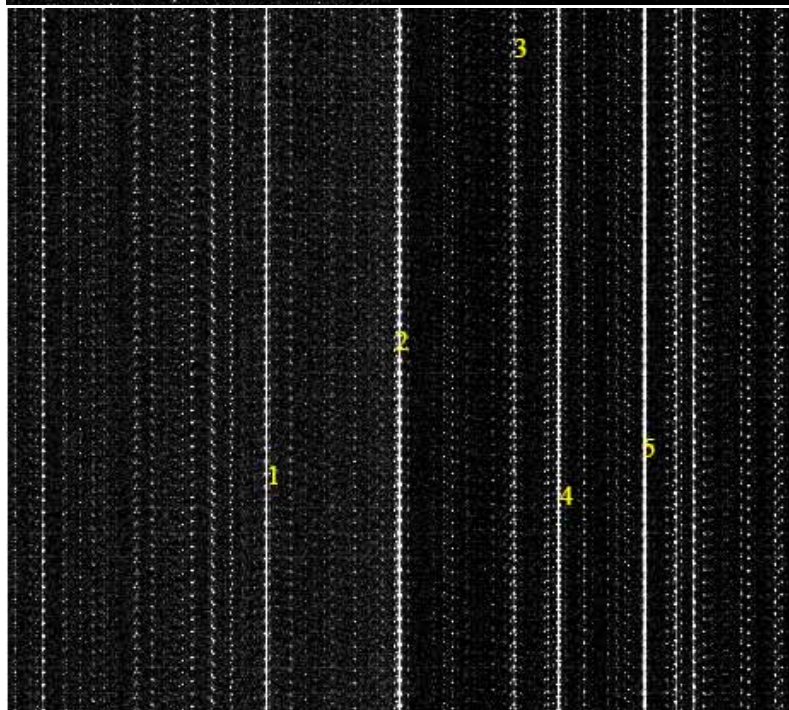


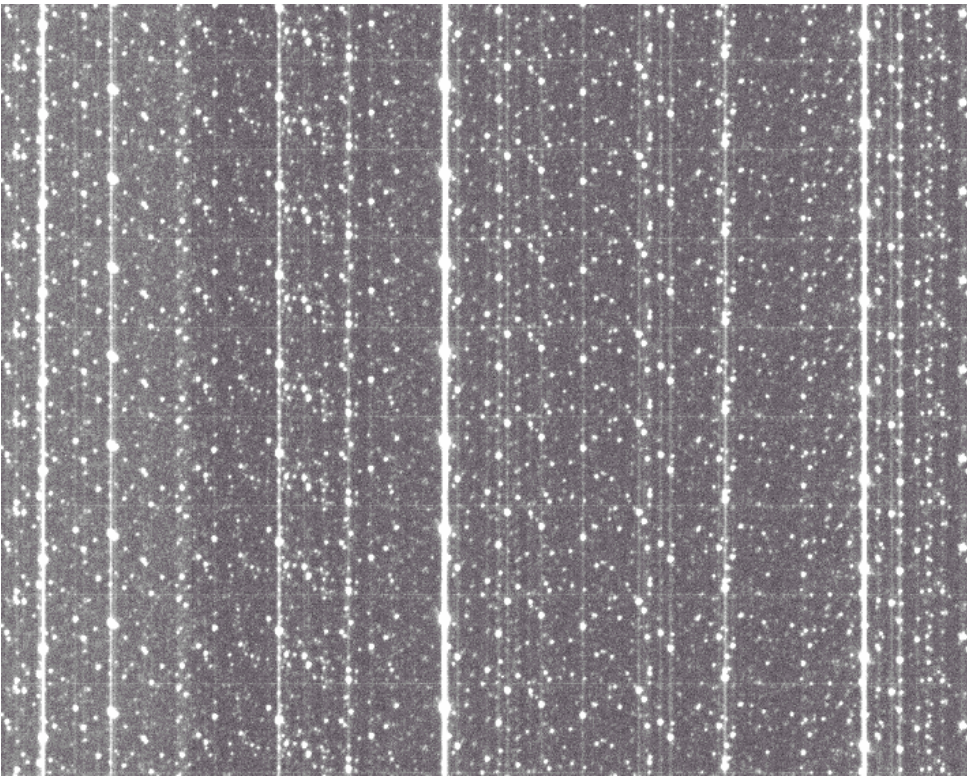
TAOS data

Integrate for 200 ms and then read out 32 rows of pixels, with the shutter remains open

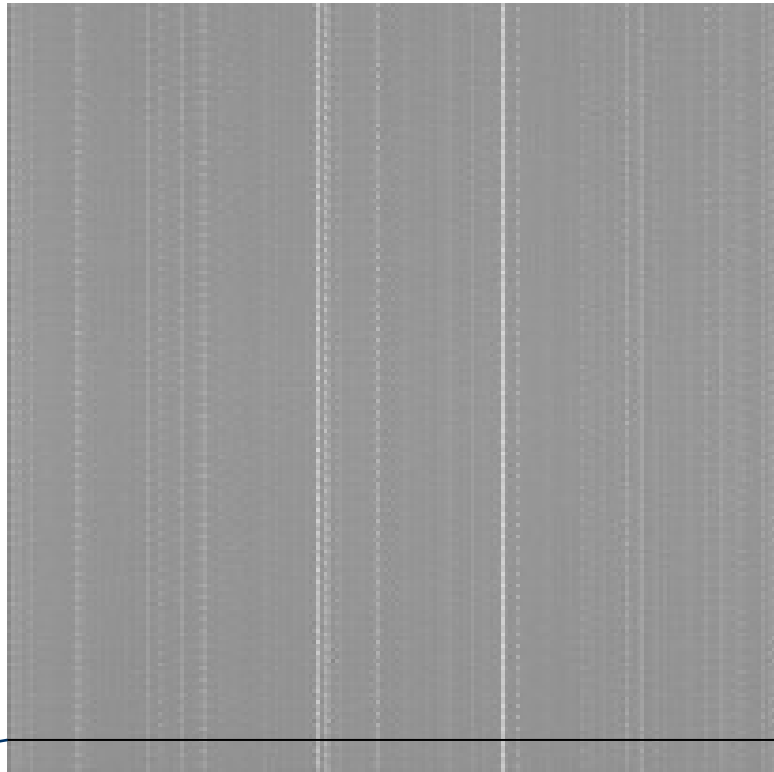
The sequence continues, so each star appears as a series of dots
→ 'zipper'

'Fake' neighboring stars and skies!





A section of an actual
TAOS zipper image



Event Detection --- Rank Statistics

- Use the rank, instead of the flux, to quantify the light curve

$$Z_w = \log_{10}(S^4) - \log_{10}\left(\prod_{i=1}^4 W_i\right)$$

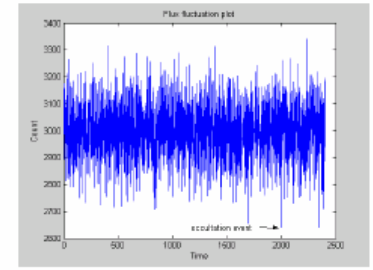
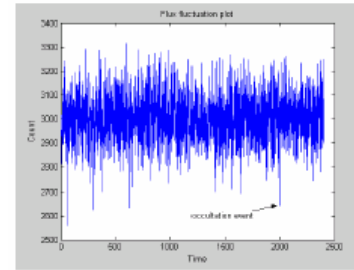
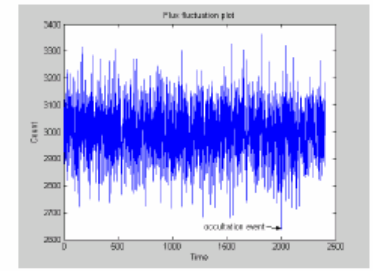
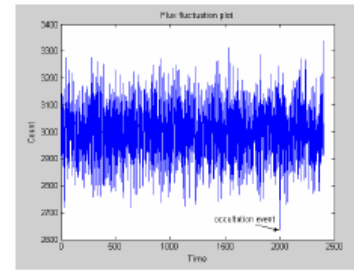
- A true occultation event should have the lowest rank in **all** telescopes

no need for highly accurate flux

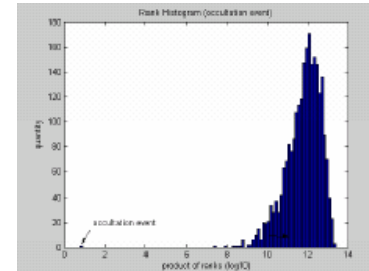
→ speed

conditional probability

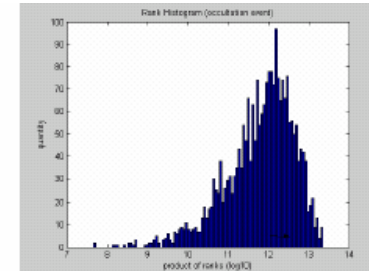
→ low false rates



Simulated light curves by each of the four telescopes

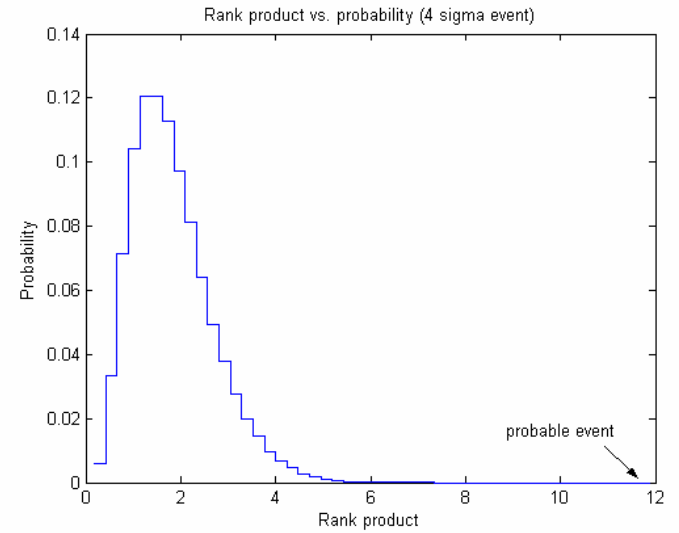
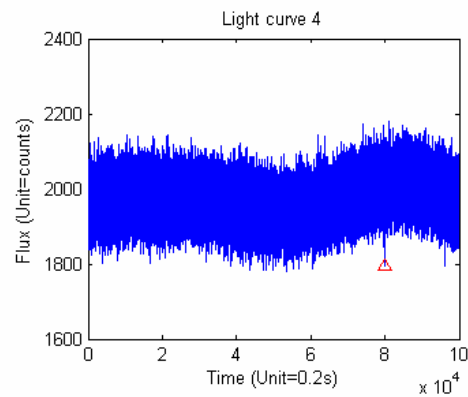
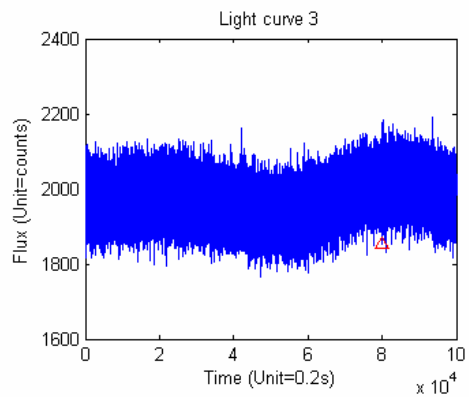
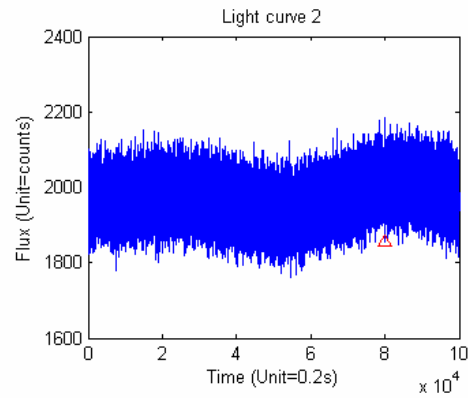
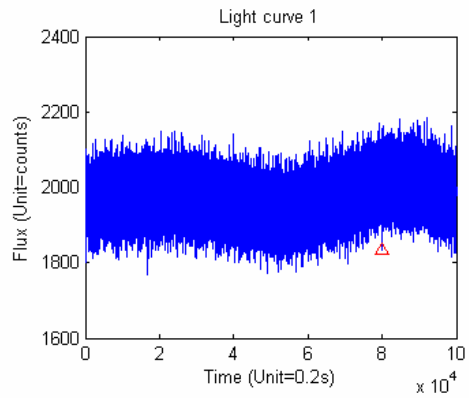


With occultation



Without

Ranking statistics



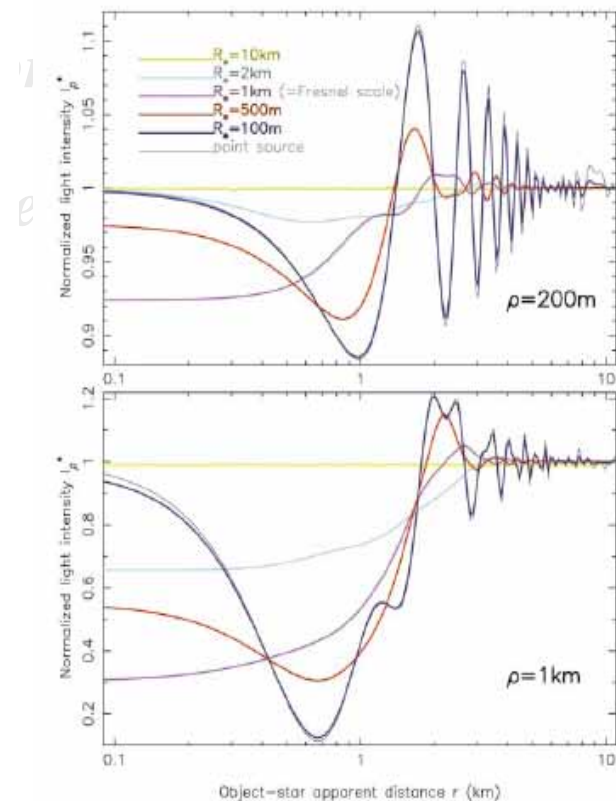
← Higher ranking

- 11:30—11:45 **IIb-3** S. K. King
TNO occultation survey: event rate, simulation & interpretation
- 11:45—12:00 **IIb-4** C. Y. Wen
TAOS Software Overview: A Robotic System
- 10:00—10:15 **IIIb-3** S. Mondal
Stellar angular diameters and occultation by KBOs

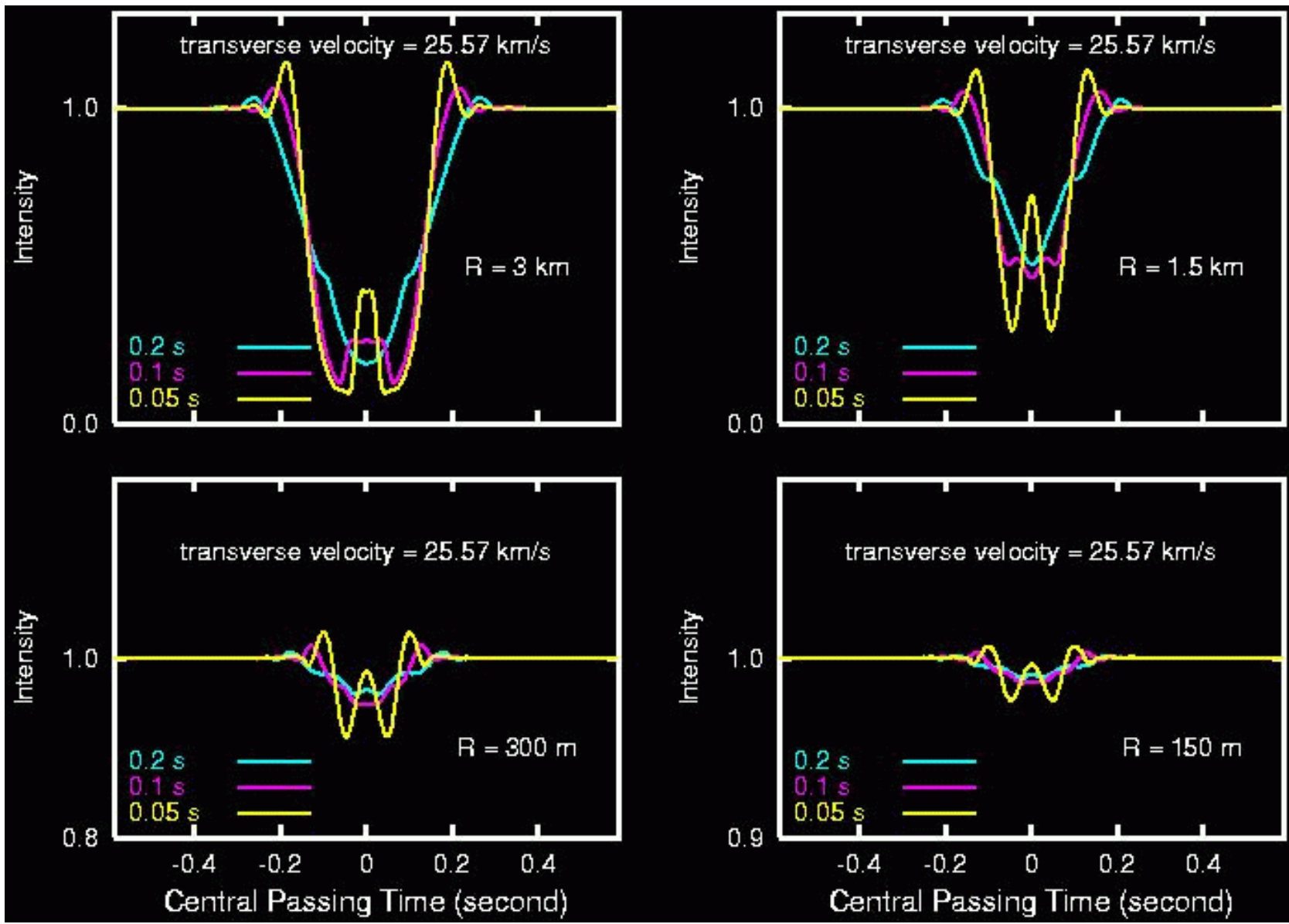
Alas, an occultation is not a simple block of starlight.

If the KBO has a small angular size (a small diameter or a large heliocentric distance) compared to the background star

→ (Fresnel) diffraction effects



KBO: circular @ 50 AU, Target star: A0 (T=9790 K, black body)
Spectral properties + different sampling rate + point source

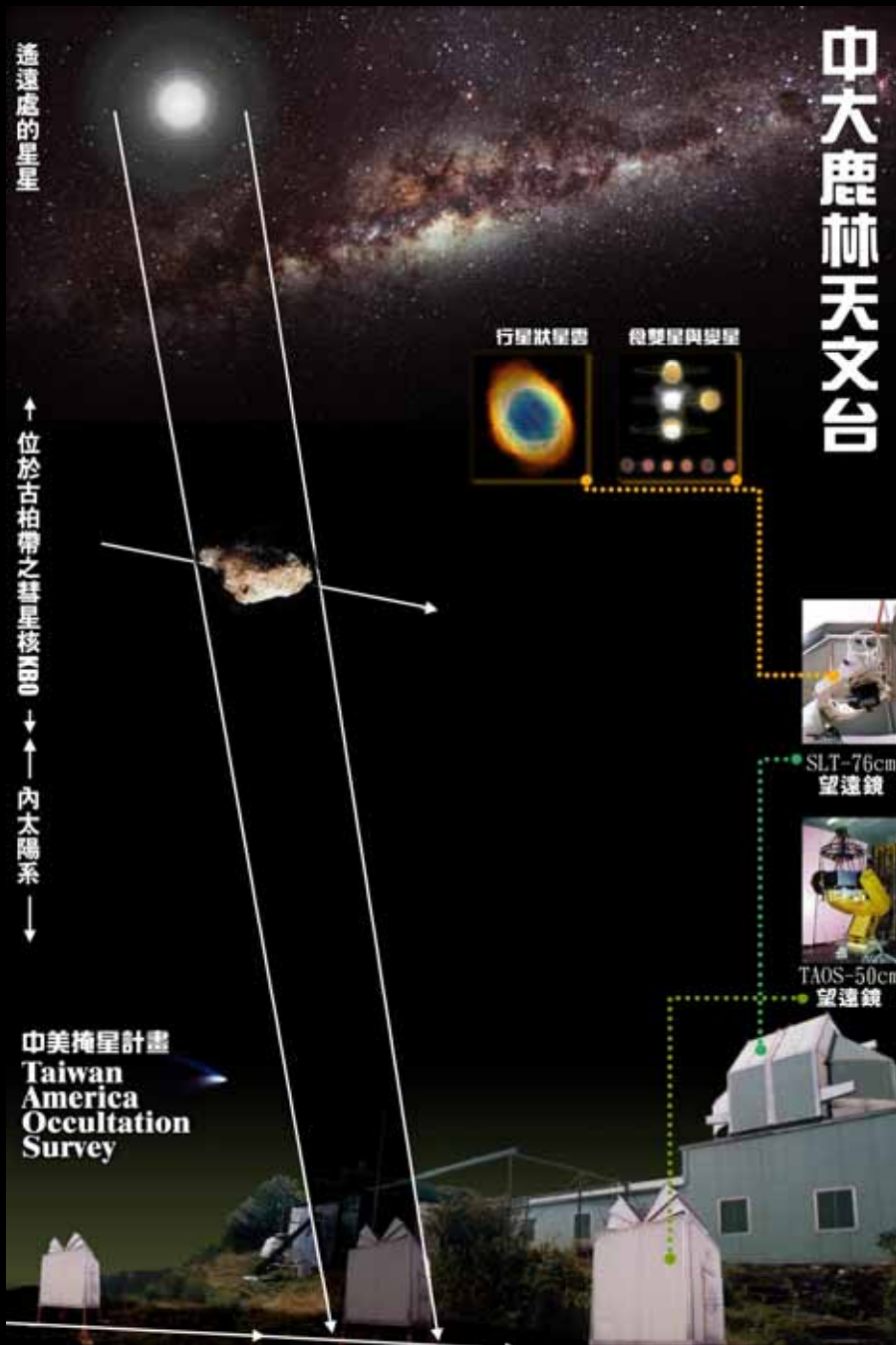


- 10:00—10:15 **IIIb-3** S. Mondal
Stellar angular diameters and occultation by KBOs
- *11:15—11:30 **IVb-2** J. S. Liang
X-Ray Source as a TNO Occultation Survey Target
- 11:30—11:45 **IVb-3** T. Lee
Possible Improvements of TAOS Performance

A much efficient camera system --- the frame-transfer CCD

Better telescope optics

...



The TAOS systems have been taking scientific data since last winter.

Routine survey with 4 telescopes will begin by this fall.

The system will also respond to GRB alerts.

Stellar variability on (sub)second time scales can be explored.

Stay tuned!