High Frequency of Candidate Companions around Planetary Systems with High Obliquity

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Outline

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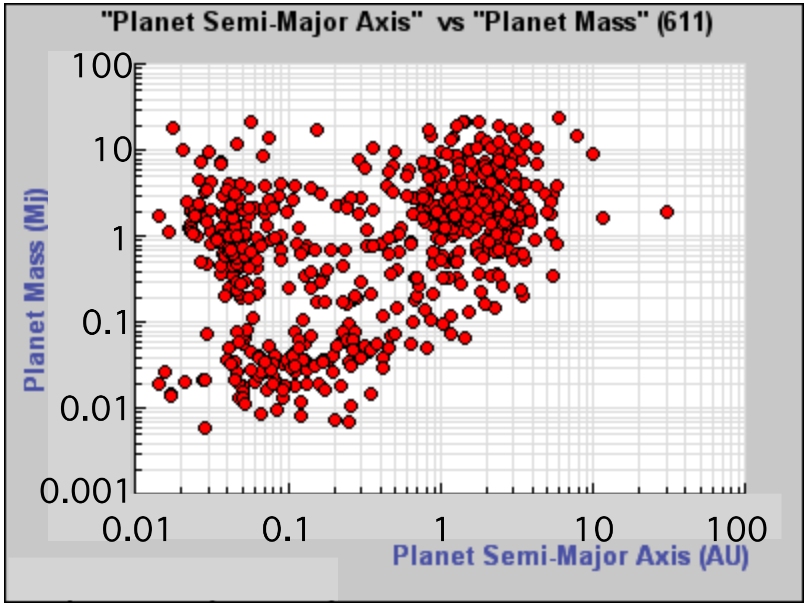
  - Diversity of Planetary Orbits
  - Planet Migration Mechanisms
  - Motivation for Direct Imaging
- Subaru HiCIAO Observations
  - Targets
  - Methodology for Testing Planetary Migration Models
- Results and Implications
- Future Prospects and Summary

Diversity of Planetary Orbits

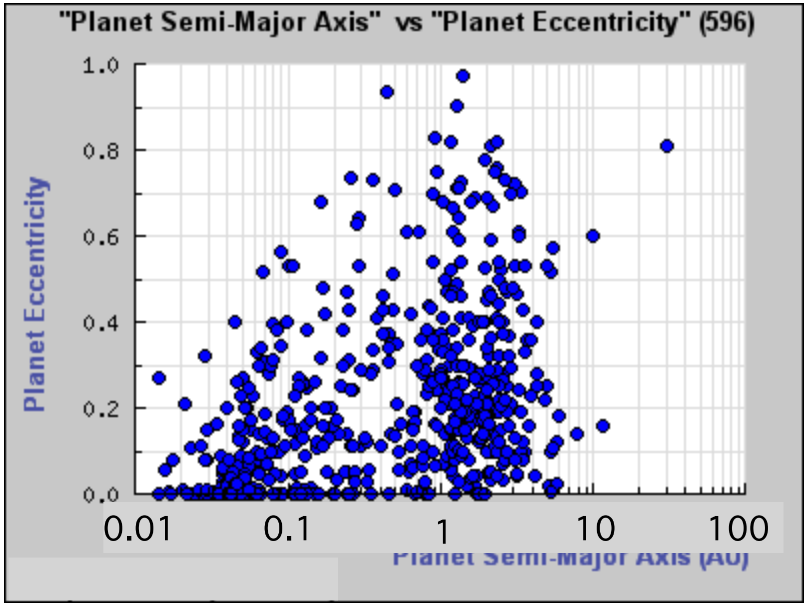


Mass Distribution

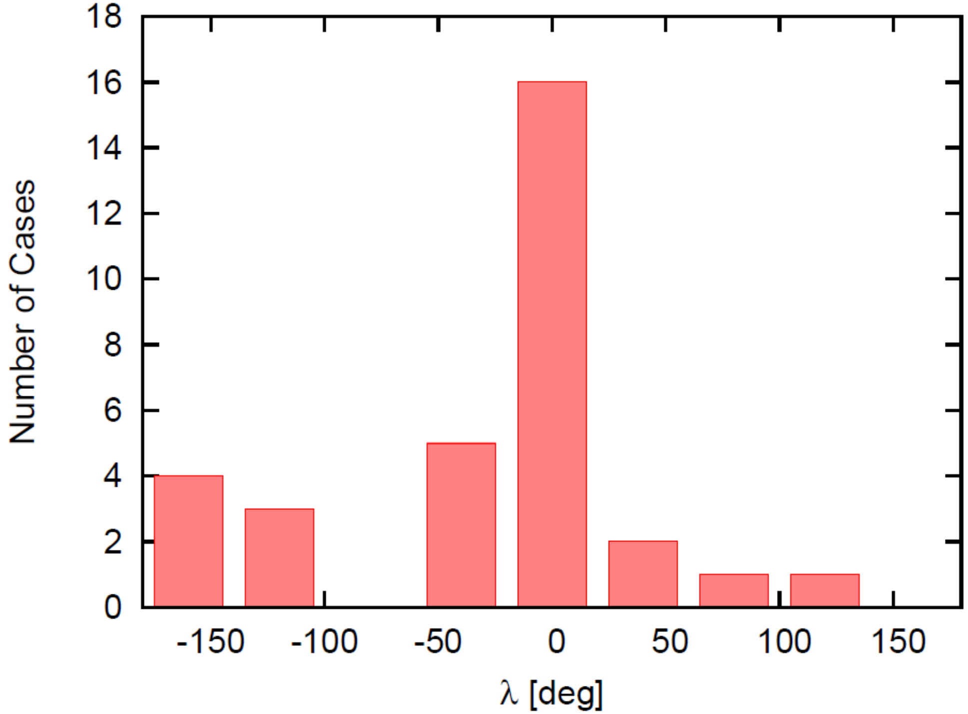
Close-in planets are common.

Eccentric planets are common.

Eccentricity Distribution

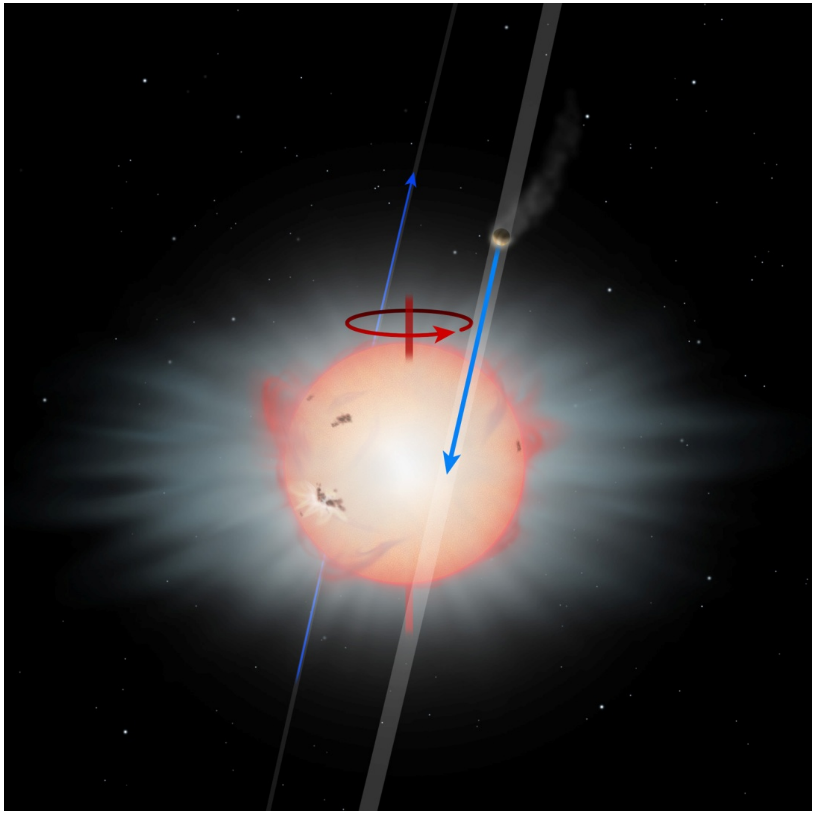


Diversity of Planetary Orbits



Obliquity Distribution

Tilted/retrograde planets are not rare.

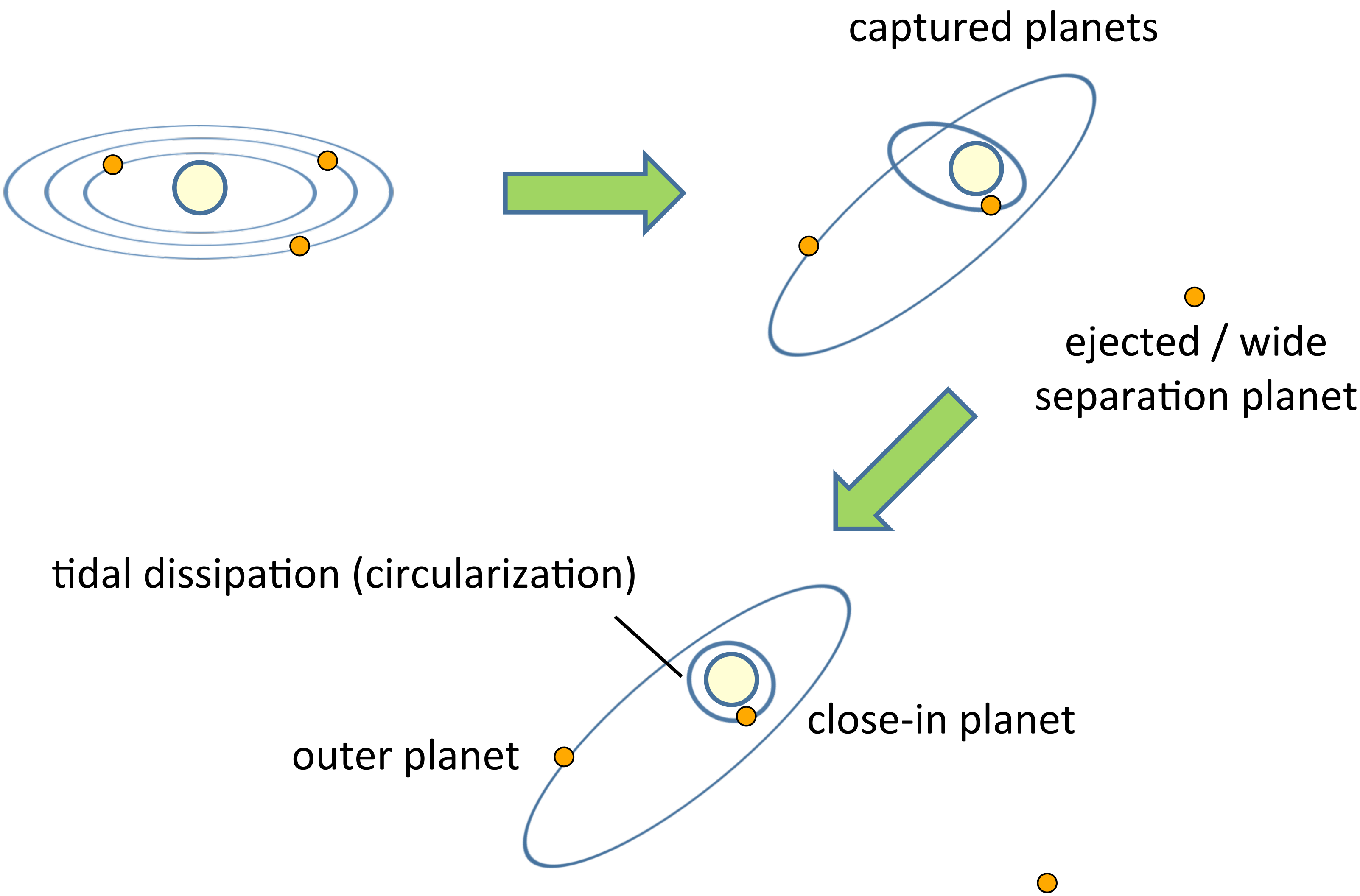


(cf. Talk by Teruyuki Hirano)

How do tilted/retrograde planets form?

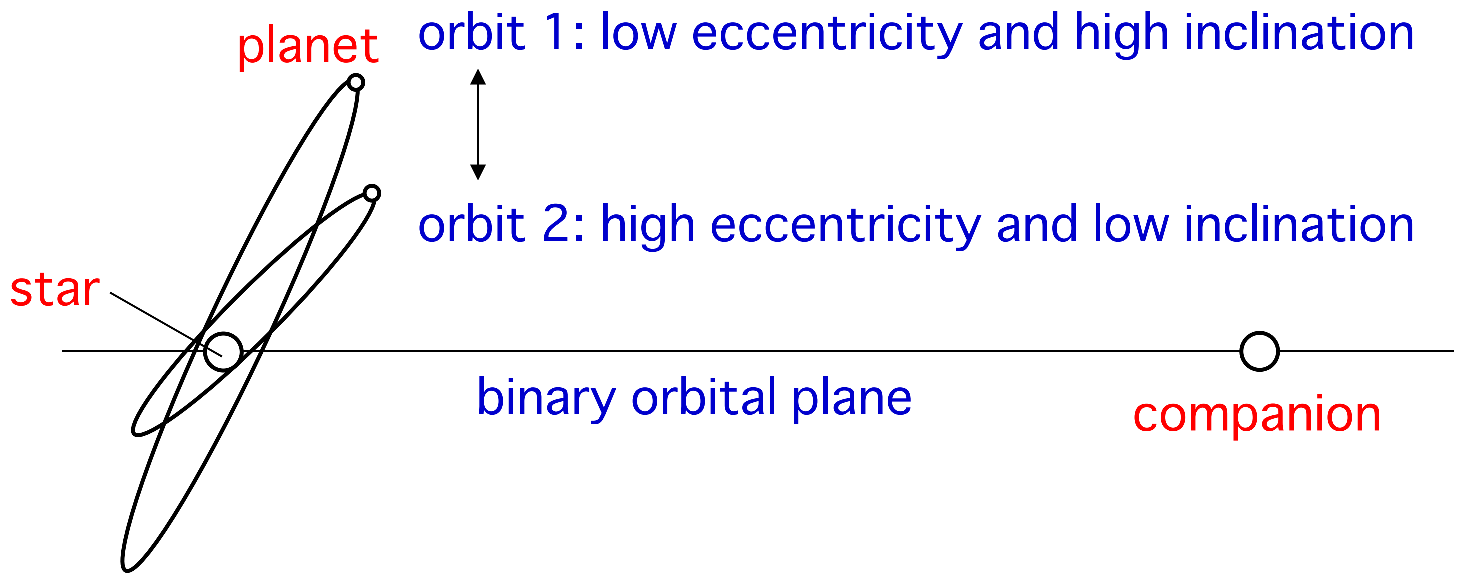
- "Standard core accretion model" cannot explain their orbits
  - ✓ This model predicts well-aligned planets
- Two possible models consider interaction between
  - ✓ planet-planet (planet-planet scattering models)
    - Nagasawa+ 2008, Chatterjii+ 2008, etc
  - ✓ planet-binary companion (Kozai migration models)
    - Wu & Murray 2003, Fabrycky & Tremaine 2007, etc
  - ✓ Both models predicts tilted/retrograde planets

Planet-Planet Scattering



Kozai Migration

Oscillation of orbit of an inner planet due to secure perturbation from an outer companion *(Kozai mechanism)*



Planet migrates inward via tidal dissipation (circularization) when its eccentricity is high.

Motivation for Direct Imaging

planet-planet scattering

Additional information from direct imaging!

Kozai migration

Search for outer counterpart is important to understand migration mechanisms for each system

Observation in SEEDS-RV Sub-category

- Members: N. Narita, Y. Takahashi, B. Sato, R. Suzuki
- Targets: known planetary systems such as,
  - ✓ Very famous systems
  - ✓ long-term RV trend systems
  - ✓ Giant systems
  - ✓ Eccentric planetary systems
  - ✓ Transiting planetary systems (including tilted systems)
- 25+ systems observed
  - ✓ including 10+ transiting planetary systems (1st epoch)

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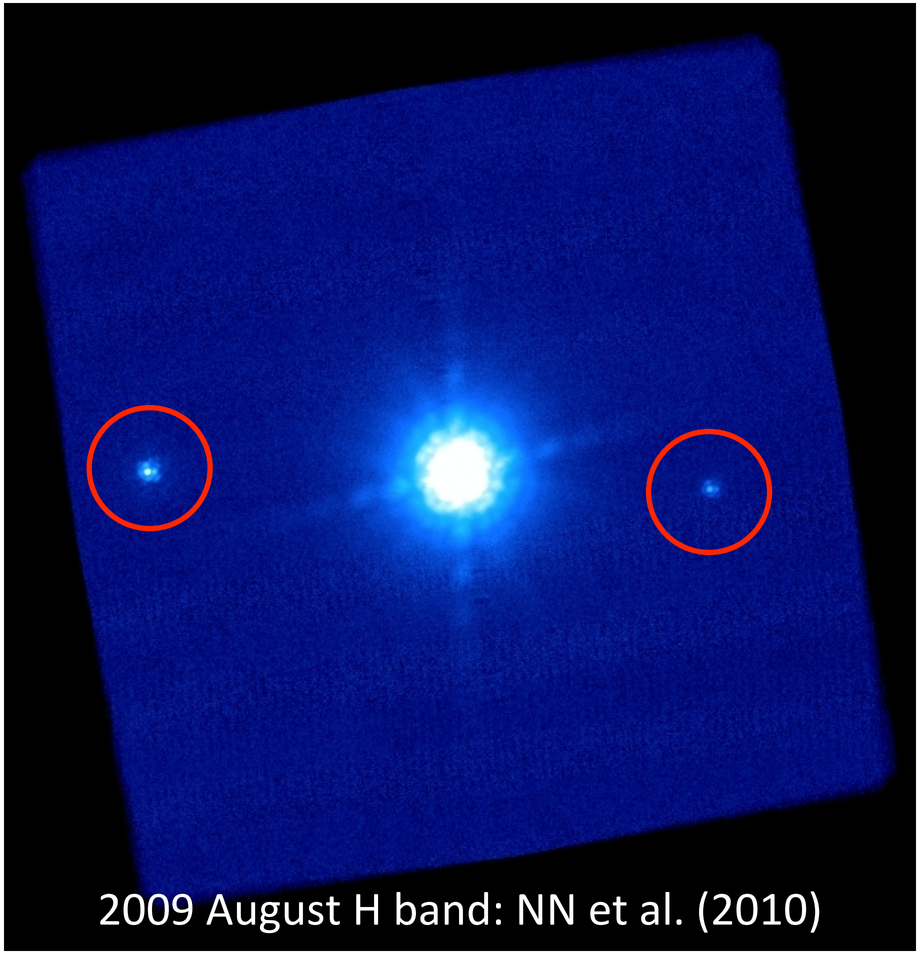
Target List of This Talk

total 12 systems with a tilted or retrograde planet

Procedure to Test Migration Models

- Step 1: Search for candidate companions
- If no companion exists
  - ✓ Kozai migration by a binary companion is excluded
- If a candidate exists -> Step 2: Check true binarity
  - ✓ need a confirmation of true binary nature
    - chance alignment probability (by Caballero+2008)
    - common proper motion (by 2nd epoch obs)
    - common distance (by spectral type)
- Step 3: Test feasibility of a Kozai migration scenario

Example of Results: HAT-P-7



CAP of 2 background stars: 0.00074%

Characterization of Candidates

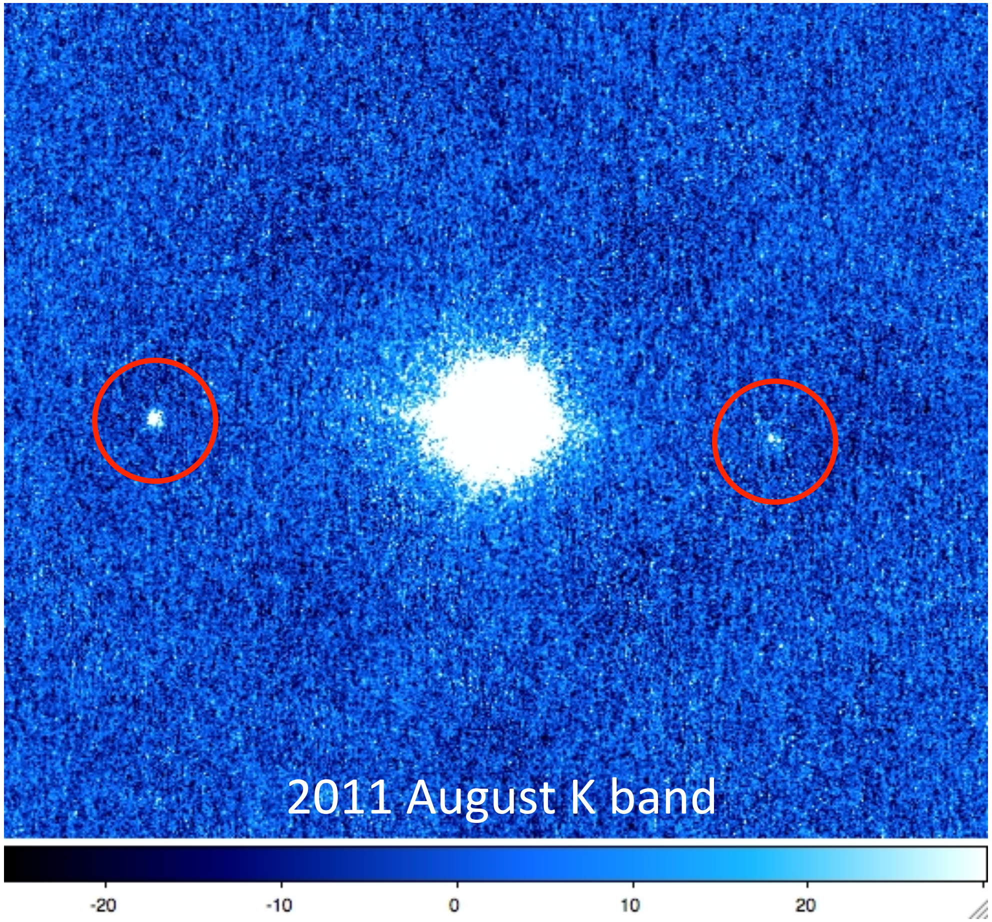
Parameter	HiCIAO (H) 2009 August 6 Value	Error	AstraLux (i')[‡] 2009 October 30 Value	Error	AstraLux (z')[‡] 2009 October 30 Value	Error
West (fainter)						
apparent magnitude [mag]	16.92	0.06	>18.65	–	>18.55	–
separation angle ["]	3.14	0.01				
position angle [°]	266.30	0.37	–	–	–	–
Estimated Spectral Type and Mass [$M_\odot$]		M9V-L0V (0.078-0.088)				
East (brighter)						
apparent magnitude [mag]	15.12	0.04	18.50	0.21	17.43	0.09
separation angle ["]	3.88	0.01	–	–	3.82	0.01
position angle [°]	89.81	0.30	–	–	90.39	0.11
Estimated Spectral Type and Mass [$M_\odot$]		M5V-M6V (0.17-0.20)				

projected separation: ~1000 AU

Based on stellar SED of Kraus and Hillenbrand (2007).

Assuming that the candidates are main sequence stars at the same distance as HAT-P-7.

Confirmation of True Binarity in Progress



At least, the bright candidate seems to have CPM

We will also obtain J, H, Ks, L' band images to determine spectral type

Tentative Results

- This is the first high-contrast direct imaging survey of faint companions to tilted/retrograde planetary systems In the world
- 12 targets were observed
  - 8 systems have candidate companions with low (<0.1%) CAP
  - 2 systems have candidate companions but with high CAP
  - 2 systems have no companion
- Tentative conclusion: relatively high frequency of candidate companions around planetary systems with high obliquity (Narita, Takahashi, et al in prep.)

What We Need to Do Next

- It may be common that tilted planetary systems have outer companions, but those are still candidates
- We need further observations to confirm CPM and distance
- After the confirmation, we can learn frequency of binary companions around tilted/retrograde planetary systems and then we can compute frequency of Kozai migration
- This study will help us to understand formation mechanisms of tilted/retrograde planetary systems by observations

Further Studies to Understand Planetary Migration

1. Extend targets to ALL close-in planets

   ✓ The current targets are only limited to tilted systems

   ✓ It is a subset of planetary systems with close-in planets

   ✓ It is important to extend targets to understand an entire picture of planetary migration of close-in planets

   ✓ Especially planetary systems in Southern hemisphere would be interesting targets (-> Gemini/NICI)

Further Studies to Understand Planetary Migration

2. Extend targets to smaller planets

- ✓ The current targets are only limited to Jovian planets
- ✓ Subaru IRD and TMT will enable us to measure Rossiter-McLaughlin effect of smaller (Earth-like and Neptune-like) planets
- ✓ At that time, high-contrast direct imaging of outer region of those targets are also important

Summary

- We conducted the first high-contrast direct imaging survey of companions around tilted/retrograde planetary systems
- Based on 1st epoch observations of 12 targets, we found candidate companions with low (<0.1%) chance alignment probability in 8 planetary systems
- Confirmation of common proper motion is in progress
- We will present a frequency of true companions around tilted/retrograde planetary systems and a frequency of Kozai migration in the future