Planetary Systems Hosted by Evolved Stars

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R\(_*\)\(\sim\)10R\(_\odot\)

M\(_*\)\(\sim\)2-3M\(_\odot\)

Giants

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Mass of a planet-host star

http://exoplanet.eu

Not harvested yet
Targeting Evolved Stars to Search for Planets around Intermediate-Mass Stars

A4V

Small $N_{\text{line}}$

Broad lines ➔ low RV precision

G2V (Sun)

Many sharp and deep lines ➔ high RV precision

Distribuion of planet-host stars

BA dwarfs

FGK dwarfs

GK giants

M dwarfs

Faint in visible ➔ infrared spectrograph (e.g., Subaru/IRD)

High RV precision, but larger stellar noise

Our targets (1.5-5$M_\odot$)
East-Asian Planet Search Network (EAPSNET)

- Japan: OAO 1.88m Tel., ~50-70 nights/yr
  - 300 GK giants (V<6), since 2001
  - Fiber-fed and slit, $I_2$ Cell, $\delta_{\text{RV}}$~2--4 m/s

- China: Xinglong 2.16m Tel., ~40 nights/yr
  - 100 GK giants (V~6), since 2005
  - Fiber-fed, $I_2$ Cell, $\delta_{\text{RV}}$~8 m/s

- Korea: BOAO 1.8m Tel., ~2 weeks/yr
  - 190 GK giants (V<6.5), since 2005
  - Fiber-fed, $I_2$ Cell, $\delta_{\text{RV}}$~7 m/s

- Japan: Subaru 8.2m Tel.
  - >200 GK giants (6.5<V<7), since 2006
  - Slit, $I_2$ Cell, $\delta_{\text{RV}}$~3 m/s

- Turkey & Russia: TUBITAK 1.5m Tel.
  - 50 GK giants (V~6.5), since 2008
  - Slit, $I_2$ Cell, $\delta_{\text{RV}}$~10 m/s

~30 planets and BDs have been found so far by the network
(e.g. Sato et al. 2013)
A Highly Eccentric Planet: HD120084 b

- $M_2 \sin i = 4.5 \, M_J$
  - $a = 4.3 \, AU$
  - RMS = 5.8 \, m \, s^{-1}$

- $e = 0.66$

- $K_1 = 53 \, m \, s^{-1}$
  - $P = 2082 \, d$
  - $e = 0.66$

- $m_2 \sin i = 4.5 \, M_J$

- $G7III, \, M_* = 2.4 M_\odot$

- $M_2 \sin i$ is below $13M_{\text{JUP}}$ with 99% confidence regardless of uncertainties in $K_1$ and $e$

- Analysis of long-term RV trend excludes existence of companion with $>13M_J (>80M_J)$ within $\sim 36 AU (~90AU)$

Currently Known Properties of Planets around Intermediate-Mass Evolved Stars

• **Occurrence rate of giant planets**
  – increases as stellar mass at least up to $\sim 1.9 M_{\odot}$ (~10–20%; e.g. Johnson+ 2007; Bowler+ 2010)
  – but decreases for $>3 M_{\odot}$ (Sato+ in prep.)

• **Planet-mass distribution**
  – super-massive ($>5 M_J$) planets are more abundant around more massive ($>2 M_{\odot}$) giants (e.g. Lovis & Mayor 2007)

• **Semimajor-axis distribution**
  – almost all the planets found around IM evolved stars reside beyond $a \sim 0.6$ AU (e.g. Sato+ 2008; Johnson+ 2007)

• **Planet-metallicity correlation**
  – unclear for evolved stars (e.g. Pasquini+ 2007; Takeda+ 2008; Mortier+ 2013)
Detection Limit for Planets around Giants

- $K_1 = 40\text{m/s} @ 2M_\odot$, Completeness ~100%
- $K_1 = 10\text{m/s} @ 2M_\odot$, Completeness <30%

RV jitter of giants is 10-20 m/s

Unexplored or not-well explored region
Next Three-Year Program at OAO

- ~50 nights/yr from 2013B to 2016A are awarded

- Targets – planets in unexplored or not-well explored region around giants
  - **Lower**-mass planets
    - Search for planets with $m_p \sin i \sim 1-2M_J$ within 5AU
  - **Short**-period planets
    - Intensive search for planets with $m_p \sin i \sim 40M_E-2M_J$ and $P<40d$
  - **Long**-period planets
    - Estimate frequency of giant planets and BDs with $a>\sim 5-10$AU
  - **Multi**-planetary systems
    - Confirm candidates of multi-planetary systems

*These are only detectable by Doppler technique at present*
LOWER-MASS, SHORT-PERIOD PLANETS
Selecting Planet-Host Candidates

\[ \frac{K_{\text{obs}}}{K_{\text{osc}}} = 2.5 \]
Currie 2009

- New candidates
- Known planets
How are low-mass planets are detectable around GK giants?

Short-period super-earths are detectable

Sato et al. 2013

Raw RV data

1-night binned

RV data from Ando et al. (2010)
MULTI-PLANET SYSTEMS
Multi-Planet Systems around Evolved Stars

• Importance of multi-planet systems (e.g. Ford 2006)
  – Evidence of orbital migration (disk-planet interaction, planet-planet scattering)
  – Setting constraint on planetary mass (orbital inclination) by taking account of orbital stability

• Several multi-giant-planet systems have been found so far
  – 24 Sextantis (2:1; Johnson et al. 2011)
  – HD 102272 (4:1?; Niedzielski et al. 2009)
  – BD+20 2457 (3:2?; Niedzielski et al. 2009)
  – HD 4732 (Sato et al. 2013)
  – etc.

↔~30-50% of giant planets around solar-type stars are in multi-planetary systems (Fischer et al. 2001; Wright et al. 2007, 2009)
A Double Planetary System: HD4732

- Observable period from OAO is limited due to low δ (~25°) ➔ collaboration with AAT
- Set upper limit on planetary mass by orbital stability analysis ➔ \( m_{b,c} < 28M_J \) \((i > 5°)\)

![Graph showing observable period and eccentricity](image)


**Legend**
- **black**: OAO
- **cyan**: AAT

**Graph Details**
- **K0IV, \( M_*=1.7M_\odot \)**
- **b**: \( \text{msin}i=2.4M_J, P=360\text{d} \)
- **c**: \( \text{msin}i=2.4M_J, P=2732\text{d} \)

**Plot**
- **Semimajor axis of planet c (AU)**
- **Eccentricity of planet c**
- **PV (m/s)**
- **JD-2400000**

**Color Legend**
- **stable**
- **unstable**
Best-fit orbits of 2-Keplerian model (b:1.45AU, 21M\textsubscript{JUP}; c:2.01AU, 12M\textsubscript{JUP}; Niedzielski+ 2009) are unstable (Horner+ 2014) unless they are retrograde.
Summary

• OAO Planet Search Program
  – ~30 planets/BDs have been found around IM giants so far

• Targets of the next 3yr program at OAO
  – Lower-mass planets, short-period planets, distant planets, multi-planet systems, which have not been well explored yet