Properties of Exoplanets: from Giants toward Rocky Planets & Informing Coronagraphy

Collaborators:
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Chris Tinney, Hugh Jones, Brad Carter
Greg Laughlin, Doug Lin, Shigeru Ida, Jack Lissauer, Eugenio Rivera

- Stellar Sample -
1330 Nearby FGKM Stars
(~2000 stars total with Mayor et al.)

Star Selection Criteria:
- V\text{mag} < 10 mag
- No Close Binaries
- Age > 2 Gyr

Target List: Published

H-R Diagram

Lick, Keck & AAT
Michel Mayor & Didier Queloz

First ExoPlanet

Now Stephane Udry plays leadership role also.

Doppler Monitoring Begun: 1987
Uniform Doppler Precision: 1-3 m s\(^{-1}\)

2000 FGKM M.S. Stars
Three Telescopes

19 Years (6 AU)  8 Years (3.5 AU)  7 Years (3 AU)

Lick Keck Anglo-Aus. Tel.
Planets or Brown Dwarfs in Unclosed, Long-Period Orbits: Targets for Coronagraphs
HD 104304 (G9, d=12.9 pc)

- Mass = 17.20 $M_{\text{Jup}}/\sin i$
- $P = 7.5$ yr
- $K = 266$ ms$^{-1}$
- $e = 0.38$

Sep $\sim 0.3"$

HD 111031 (G5, d=30 pc)

- Mass = 2.870 $M_{\text{Jup}}/\sin i$
- $P = 16.4$ yr
- $K = 33.9$ ms$^{-1}$
- $e = 0.32$

Sep $\sim 0.2"$
Examples of Jupiter-mass & Saturn mass Planets Detected by RV
**Jupiter Mass Extrasolar Planets**

**HD 66428**
- $P = 5.3$ yr
- $e = 0.47$

$M \sin i = 2.96 M_J$

**RMS = 2.90 m/s**

$\chi^2 = 0.46$

**Year**

2001 2002 2003 2004 2005 2006

**Jupiter Mass Extrasolar Planets**

**HD 99109**
- $P = 1.3$ yr

$M \sin i = 0.52 M_J$

**RMS = 6.28 m/s**

$\chi^2 = 0.87$

**Year**

Sub-Saturn Masses: $30 - 100 M_{\text{Earth}}$

Old Doppler Precision: 3 m/s

Sub-Saturn Masses:
Detectable for $P < 2$ Month

Multiple - Planet Systems
HD 12661: Sun-like Star

2.5 M\(_J\)  
1.9 M\(_J\)  
Weak Interactions

HD 128311  
2:1 Resonance

K0V, 1Gy, 16 pc

<table>
<thead>
<tr>
<th>Inner</th>
<th>Outer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per (d)</td>
<td>458</td>
</tr>
<tr>
<td>Msini</td>
<td>2.3</td>
</tr>
<tr>
<td>ecc</td>
<td>0.23</td>
</tr>
<tr>
<td>(\omega)</td>
<td>119</td>
</tr>
</tbody>
</table>

\(P_c / P_b = 2.004\)  
Dynamical Resonance  
(Laughlin)
M Dwarfs have distant giant planets.

5 Mean-Motion Resonances

Implies:
- Orbital Migration
- Capture into Resonances
- Eccentricity Pumping

Coronagraphs can expect planets at 20 AU accompanied by inner giant planets.
Giant Planets: Mass Distribution

- Rise toward lower masses to $1 \, M_{\text{SAT}}$
- Sub-Saturns
  - 13/138 have $M_{pl} > 5 \, M_J$
  - $= 10\%$ of planets

Semimajor Axis Distribution

- 6.5\% occurrence
- If $dN/d\log a = \text{const}$:
  - 6\% of stars have planets 3 - 20 AU

12\% of stars Harbor Giant Planets
Orbital Period Distribution
Correction for Incompleteness
Cumming et al. 2007

Cumulative fraction

Period (days)

Number

\( dN /d\log P \sim P^\beta \)
\( \beta = +0.26 \)

Take Home:
\( dN/d\log_{10} P \)
\( = 6.5\% \)

Occurrence of Long Period Orbits
Cumming et al. 2007

<table>
<thead>
<tr>
<th>a &lt; 3 AU</th>
<th>5 AU</th>
<th>10 AU</th>
<th>20 AU</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.5%</td>
<td>11%</td>
<td>14%</td>
<td>19%</td>
</tr>
</tbody>
</table>

For: \( 0.3 < M_{pl} < 15 \, M_J \)

Cumulative percentage of stars with a palnet
\( N (<P), \) based on a power law extrapolation beyond \( P = 2000 \, d. \)
If \( \frac{dN}{d\log a} = \text{const} \):

- \( \Delta 6\% \) of stars have planets 3 - 20 AU.
- If \( dN/d\log a = \text{const} \), 6\% 20-120 AU

Most Models \( \Rightarrow \) Reservoir of Jupiters at 5-20 AU.

Few Jupiters \( a > 20 \text{ AU} \).

- Inward Migration.
- Planets left in place as disk vanishes.

Trilling, Benz, Lunine (2002)
Lin & Hs 2004
Alibert & Benz

Chemical Abundances Of Stars
Fischer & Valenti

Spectral Synthesis Modeling
1) LTE radiative transfer with Kurucz model atmospheres.
2) Least-Squares fit to spectral lines.
Chem. Abund. Analysis of 1000 stars on planet search.

Metallicity Models:
Core-Accretion Model:
More Dust $\Rightarrow$ Planet growth rate
Ida & Lin (2005)
Kornet et al. (2005)
Ed Thommes 2006

Exoplanets as a function of Stellar Mass
- 120 M dwarfs (0.3-0.6 $M_\odot$)
- 200 “A-type” Stars (1.5-2.0 $M_\odot$)
Retired A-Stars and Their Planets

HD 210702: $M_\ast = 1.85 \, M_\odot$

John Johnson et al. (2007)

John Johnson 2007
Jupiter Occurrence vs Stellar Mass

For $a < 2.0$ AU, $M_p \sin i > 0.8 M_{\text{Jup}}$, $N_{\text{obs}} > 8$

- $N_{\text{PLANETS}} = 2$
- $N_{\text{STARS}} = 167$
- $N_{\text{PLANETS}} = 10$
- $N_{\text{STARS}} = 478$
- $N_{\text{PLANETS}} = 8$
- $N_{\text{STARS}} = 89$

Beware Metallicity Effects.

5/58 @ Lick
3/31 @ Keck

Orbital Eccentricities

Tidal Circ.: $a < 0.1$ AU

- $<e> = 0.25$
- Origin of eccentricity is controversial.
- Eccentricities still high beyond 2.5 AU
Origin of Eccentricities
Planet - Planet Interactions

Simulation Time: 00.0 years
Ford & Rasio 2006

Super-Earths: 1 - 14 $M_{\text{Earth}}$
Poorly Understood Planet Domain

- Earth - Uranus:
  Gap in Mass: Factor 14

- Intermediate Masses:
  Do they Form?
  Or do planet embryos accrete gas ala Neptune?

- If They Form:
  - Terr-like: CO$_2$ Atm.?
  - Neptune-like H&He env?

- Density: 1 or 5 g cm$^{-3}$?
Gliese 436 (M2.5 V)

Periodogram

P = 2.643 day
Gliese 436:
22 Earth Masses

**Tidal Lock**
P = 2.64 d

**Composition?**
- Gaseous?
- Rock + ice?
- Rock + Fe core?

**L_{STAR} = 1/50 L_{O}**

**Atmosphere?**
- T_{front} = 650 K?
- T_{back} < 200 K?

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Gliese 436: Transits

\[ R = 3.95 R_{\text{Earth}} \]

\[ \rho = 2.0 \text{ gm/cc} \]

Butler et al. 2004; Maness et al. 2007

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**Gliese 436 Transits**

\[ R = 3.95 R_{\text{Earth}} \]

\[ \rho = 2.0 \text{ gm/cc} \]

Gillon et al. 2007
It seems likely that planets with masses within an order of magnitude of the Earth's mass will be composed primarily of ices, rocks, and iron.

Gliese 876 (M3V)

- Star Mass = 0.32 \( M_{\text{sun}} \)
- \( d = 4 \) pc
- Two Jupiters in 2:1 res.
Gliese 876: 2-Planet Fit

\[ \text{RMS} = 6.30 \text{ m s}^{-1} \]
\[ \sqrt{\chi^2} = 1.593 \]

GL 876
2:1 Mean-Motion Resonance
&
Apsidal Lock

**Inner** \[ P = 30.1 \text{ d} \]
**Outer** \[ P = 61.0 \text{ d} \]

<table>
<thead>
<tr>
<th>Msini</th>
<th>0.56</th>
<th>1.89 M_J</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>0.27</td>
<td>0.10</td>
</tr>
<tr>
<td>( \omega )</td>
<td>330</td>
<td>333°</td>
</tr>
</tbody>
</table>

Resonance Work:
- Laughlin & Chambers
- Lissauer & Rivera
- Man Hoi Lee & S. Peale
Gliese 876

- 2:1 Mean Motion Resonance
- Precession Period: 9 yr

$t/T_c = 0.00$

GJ 876: Velocities

Two-Planet Model

Laughlin et al. 2004
3-Planet Fit

Velocity Residuals to 2-Planet fit

Period = 1.94 d
M\sin i = 5.9 M_{\text{Earth}}

For i = 50 deg,
M_{PL} = 7.5 M_{\text{Earth}}

Inward of habitable zone
The HARPS search for southern extra-solar planets*  
XL Super-Earths (5 & 8 M_⊕) in a 3-planet system


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4 Observatoire de Paris, CNRS, Université Paris et Institute d'Astrophysique, PSL Research University  
5 Service d'Astrophysique de CEA/IRFU, Université Paris-Saclay, CEA, France  
6 PASP, 9157, Montevideo-Belvédère, France  

Abstract: This Letter reports on the detection of two super-Earth planets in the Gliese 581 system, already known to host a hot Jupiter. One of the planets has a mass of 5 M_⊕ and resides in the "warm" edge of the habitable zone of the star. It is thus the lowest-mass planet with a mass exceeding that of any known planet in the solar system. The other planet has a mass of 8 M_⊕ and resides at 0.25 AU from the star, inside the "cold" edge of the habitable zone. These two new planets, named Gliese 581 b and c, respectively, brought to the number of known super-Earth planets, around a mid-M dwarf, to 18.  

Key words: exoplanet individual, G dwarf, star, planetary system - techniques: radial velocities - techniques: spectroscopy

1. Introduction
M dwarfs are of primary interest for planet-search programmes. First of all, they extend the stellar parameters domain probed for planets. For high precision radial-velocity planet searches, M dwarfs are excellent targets as well, because the lower primary mass makes the detection of very light planets easier than around sun-like stars, in particular Earthmass planets in Neptune-mass planet. The minimum mass of the 3.3rd known planet is 5.03 terrestrial mass, the lowest for any exoplanet to date. Among the 3.50 M_⊕ of the microlensing candidateOGLE-2005-BLG-392Lb (Bouy et al., 2006) found as a large separation from another M dwarf, it resides at the inner edge of the habitable zone of Gliese 581. The 3.4rd planet, at 0.25 AU from the star, is also in the super-Earth category (7.2 M_⊕), and is similar in mass to the other Gliese 581 system mid-M dwarfs.

2. Planet "c":  
1) Actual Habitable Zone: 0.10–0.20 AU
Efficient IR opacity -> heating in any atmosphere (Sasselov, Selsis, Kasting, Seager, Bloch, Cuntz, 2007) (Potsdam preprint)
2) Mass: Arguably an Ice Giant: ~ Gliese 436 b, Uranus, Neptune

See Xavier Bonfils talk.

Gliese 581

<table>
<thead>
<tr>
<th>Planet</th>
<th>Orbit Radius (AU)</th>
<th>Minimum Mass (Earth)</th>
<th>Likely Mass (x 4/π)</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>0.041</td>
<td>15.2</td>
<td>19</td>
</tr>
<tr>
<td>c</td>
<td>0.073</td>
<td>5.0</td>
<td>6.4 &quot;T = 0-40°C&quot;</td>
</tr>
<tr>
<td>d</td>
<td>0.25</td>
<td>8.2</td>
<td>10.4</td>
</tr>
</tbody>
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Planet "c":  
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2) Mass: Arguably an Ice Giant:
~ Gliese 436 b, Uranus, Neptune
In a protoplanetary disk, if 6 \( M_{\text{earth}} \) of silicates accumulate into planet does it normally acquire ices too?

Outside snow line: Yes.

Witness Solar System’s – icy giants, icy moons, Pluto, KBOs. All have comparable: silicate & water.

Formation Within Snow Line: Water Delivery to Rocky Planets by hydrated asteroids & comets.

- Water Delivery: Comets & hydrated asteroids
- \( H_2O \) content vs \( r_{\text{orb}} \) from meteorites
- N-body: collisions deliver \( H_2O \)
- Jupiter ejects asteroids, preventing their delivery of water to the terrestrial planets at 1 AU.
- Continuous \( H_2O \) delivery
- Loss of \( H_2O \) by impacts ??
- Water-rich worlds common ?: 10 - 100 “Earth-Oceans”

\( \text{Water Content (Earth Oceans)} \)

Fig. 9 Histogram of the water content of 45 planets with 0.8 AU < \( a < 1.3 \) AU which formed in 44 simulations. See text for discussion.

\( \text{N-Body Planet Growth with Water Delivery} \)
Raymond, Quinn, Lunine 2004
Super Earths
Formation beyond 2 AU
Leger et al. 2004

- Ice-rock planetesimals growth
- Europa/Neptune Composition
  - Ice-rock: 50-50
- Migration inward of 1 AU

**Structure**
- Solve Interior Eqns.
  Include EOS of water + Rock mantle + Fe core
- Water is liquid at high pressure (~Europa).

**Phase Diagram of Water**

Fig. 2. Phase diagram of water (full lines). The dotted (dashed-dotted) line describes the temperature adiabatic (isothermal) cycle in the central part of a solid surface where H₂O = 2% (H₂).

**Water Worlds**
10 - 50\% H₂O

6 \(M_{\text{Earth}}\) Planets:
- 50\% H₂O
- No H₂O

- H₂O Atmosphere +
- H₂O Ocean +
- Ice Envelope (ala Neptune)

- Lower Density than rocky planets
- Distinguish water worlds from rocky worlds:
  - Radial velocity and transit
  - M, R, \(R/\text{Earth} = 2.00\)

\(\rho = 4.3 \text{ g cm}^{-3}\)

\(\rho = 7.7 \text{ g cm}^{-3}\)

Leger 2004, Raymond 2005
Detecting Rocky Planets by Doppler Measurements of Stars

Star's Wobble Velocity:
\[ K = 0.1 \text{ m/s } \left[ \frac{M_p}{M_{\text{star}}} \frac{1}{a^{1/2}} \right] \quad (M_p \text{ in } M_\oplus) \]

Benchmark:
Earth induces 0.1 m/s (at 1 AU)

Strategy:
- Achieve Doppler Precision of 1 m/s
- Choose Low Mass Stars
- Search for Short Periods (small a)
- Low mass stars have lower surface turbulence and lower oscillations

Lyot Conference
Summary

- Mass Distribution: Rises to lower masses
- Semimajor Axis Distrib.: Rises toward 5 AU - Beyond?
- Planets correlate with Metallicity & Stellar mass

Concern:
- <5% have giant planets beyond 20 AU
- ~10% of giant planets have M>5 Mjup

Occurrence of M>5 Mjup beyond 20 AU < 0.5% ??

F and A stars gold vein: Young, Massive, Metal-Rich Stars