LYOT CONFERENCE
5 JUNE 2007

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

Collaborators:

Paul Butler, Debra Fischer, Steve Vogt
Chris McCarthy, Jason Wright, John Johnson, Katie Peek
Chris Tinney, Hugh Jones, Brad Carter
Greg Laughlin, Doug Lin, Shigeru Ida, Jack Lissauer, Eugenio Rivera

NASA | University of California | SFSU San Francisco State University | NSF | USNO

-Stellar Sample -

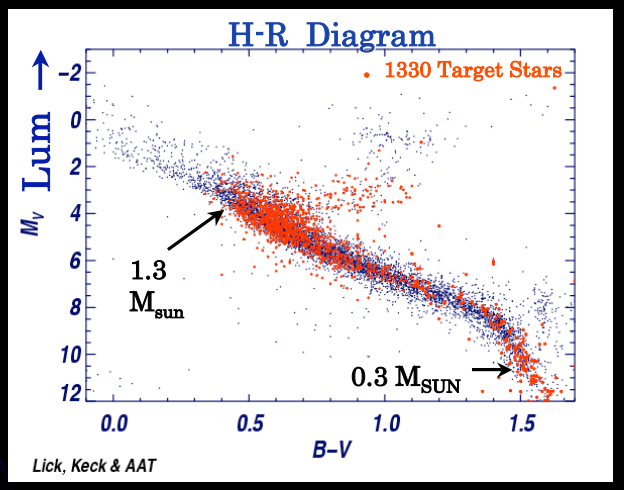
1330 Nearby FGKM Stars

(~2000 stars total with Mayor et al.)

Star Selection Criteria:

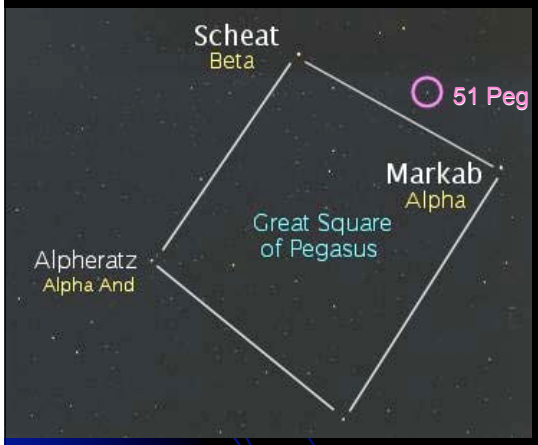
- V_{mag} < 10 mag
- No Close Binaries
- Age > 2 Gyr

Target List: Published



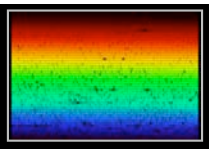
Michel Mayor & Didier Queloz

First ExoPlanet



Now Stephane Udry plays leadership role also.

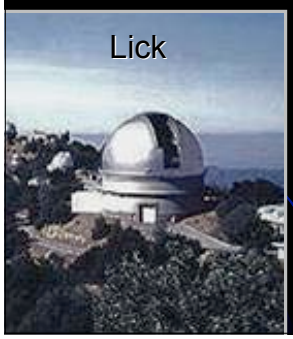
Doppler Monitering Begun: 1987



Uniform Doppler Precision: 1-3 m s^{-1}

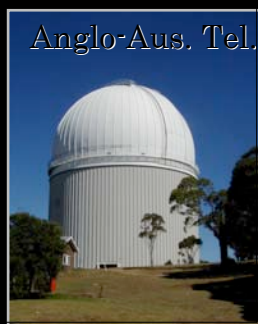
2000 FGKM M.S. Stars
Three Telescopes

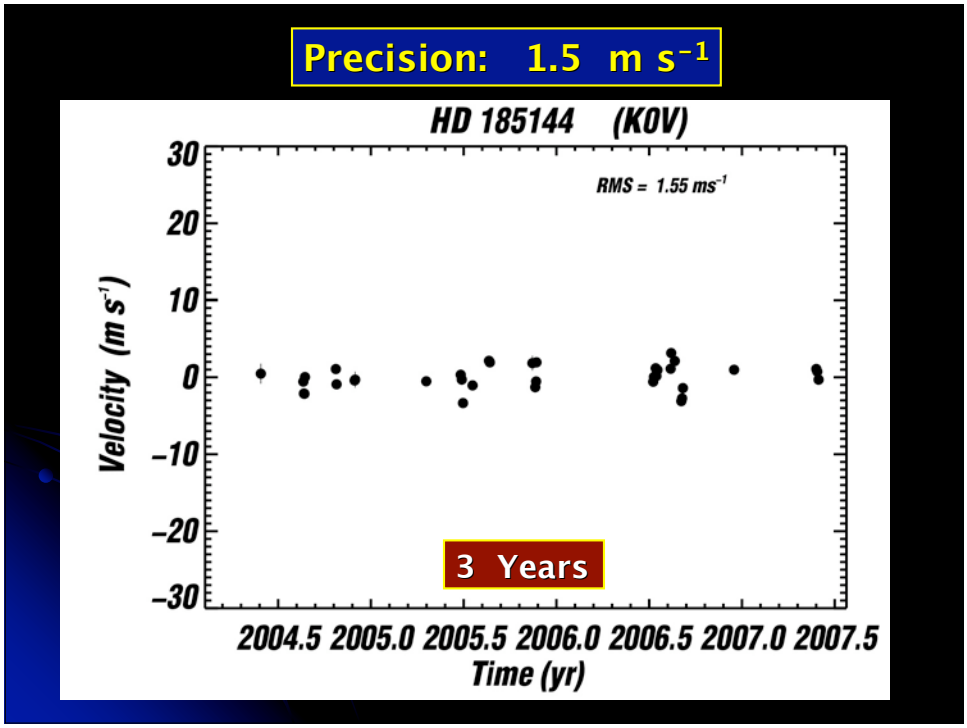
19 Years
(6 AU)

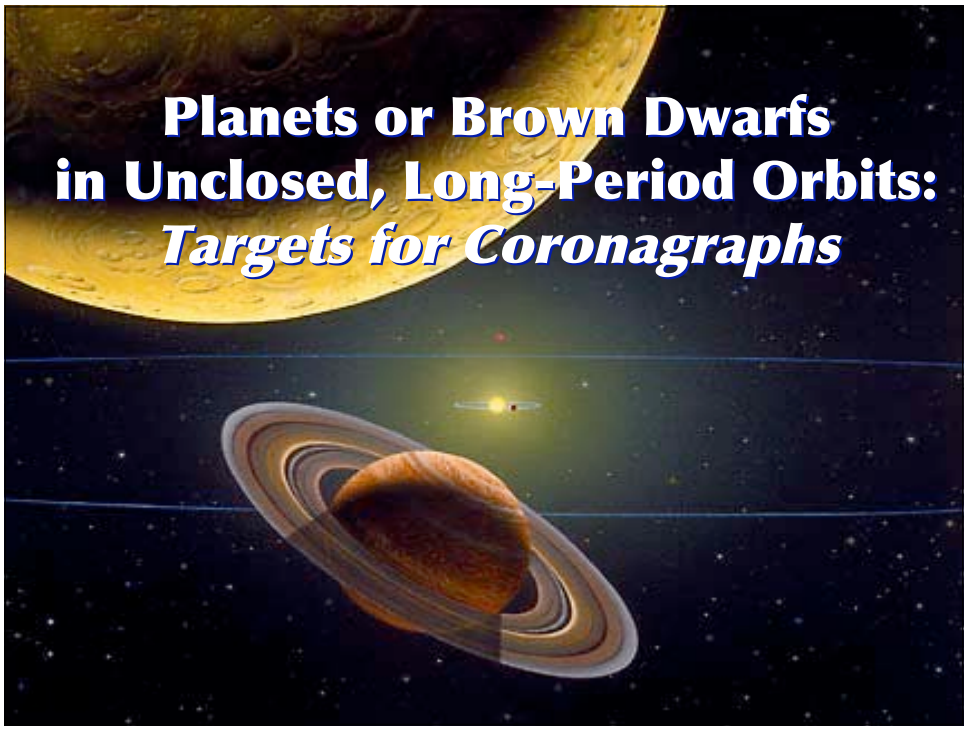


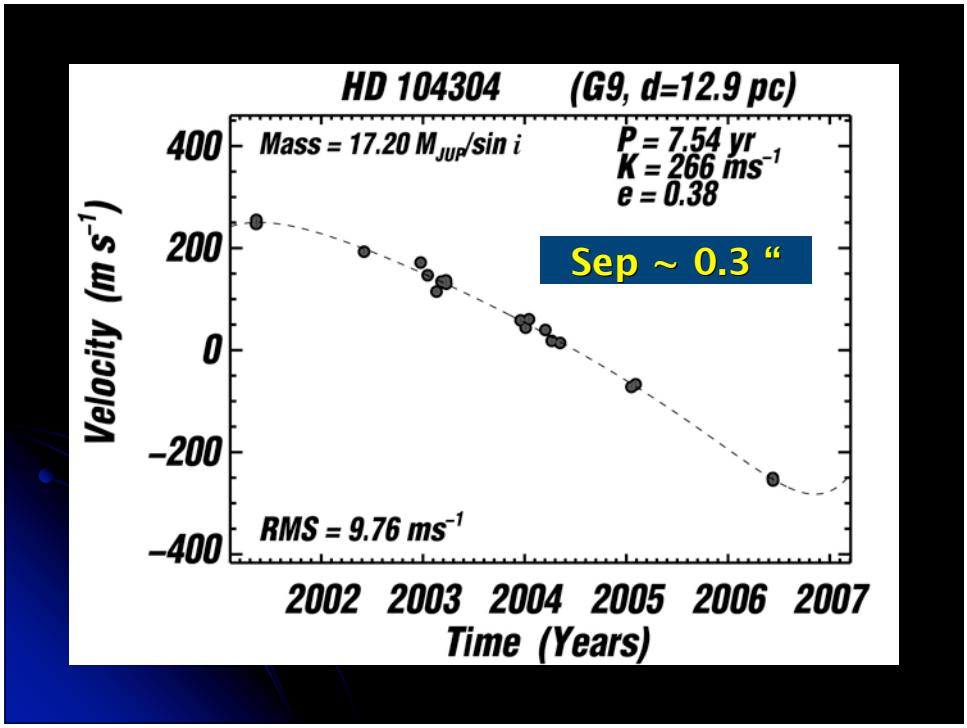
8 Years
(3.5 AU)

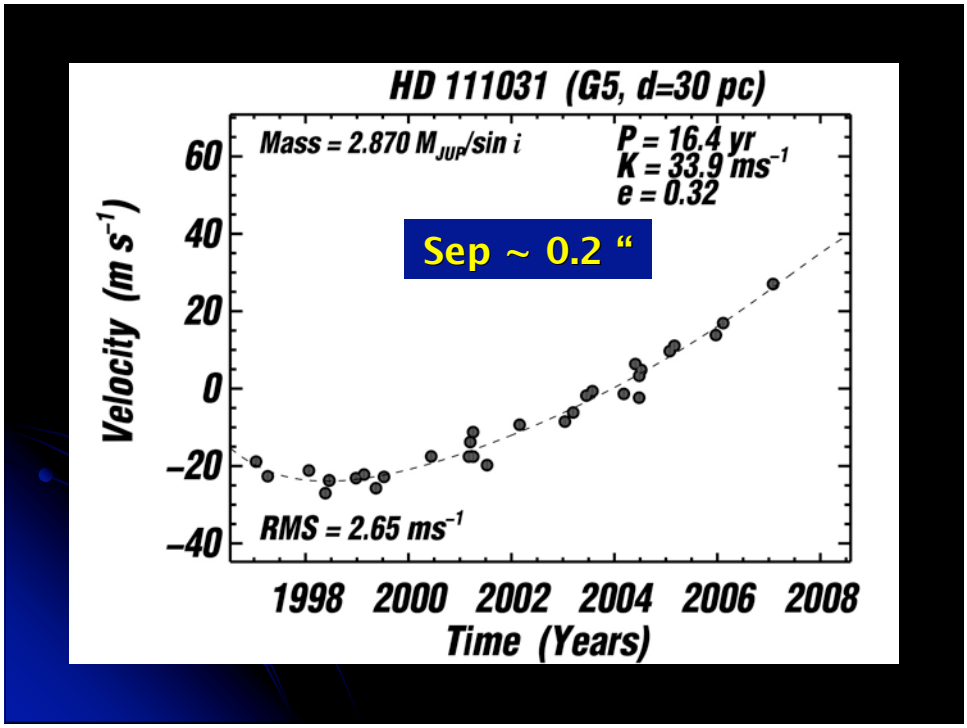
7 Years
(3 AU)

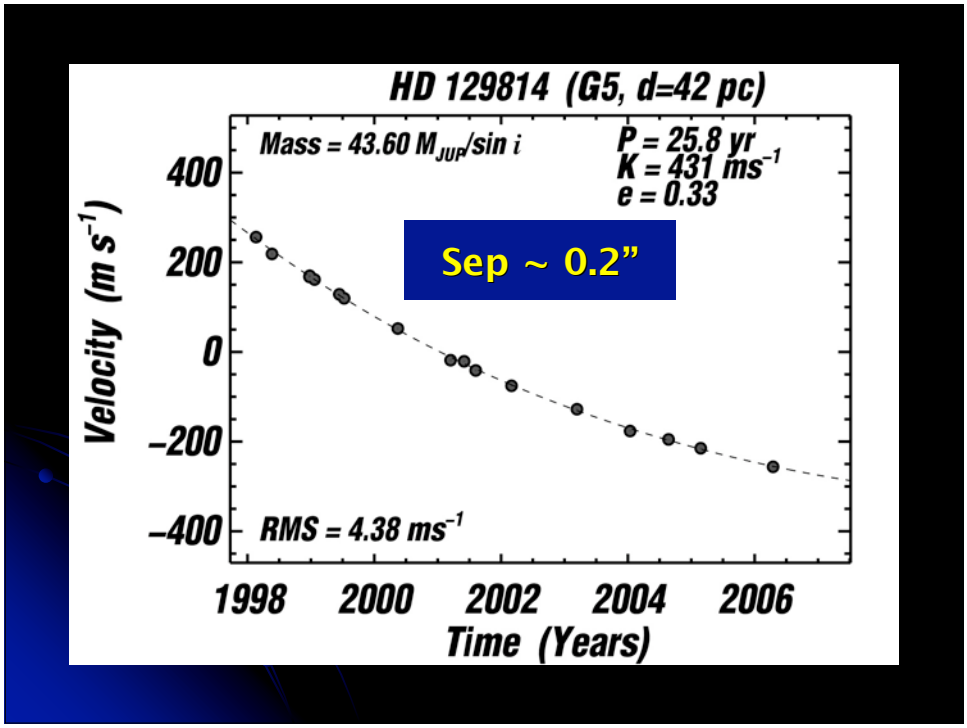


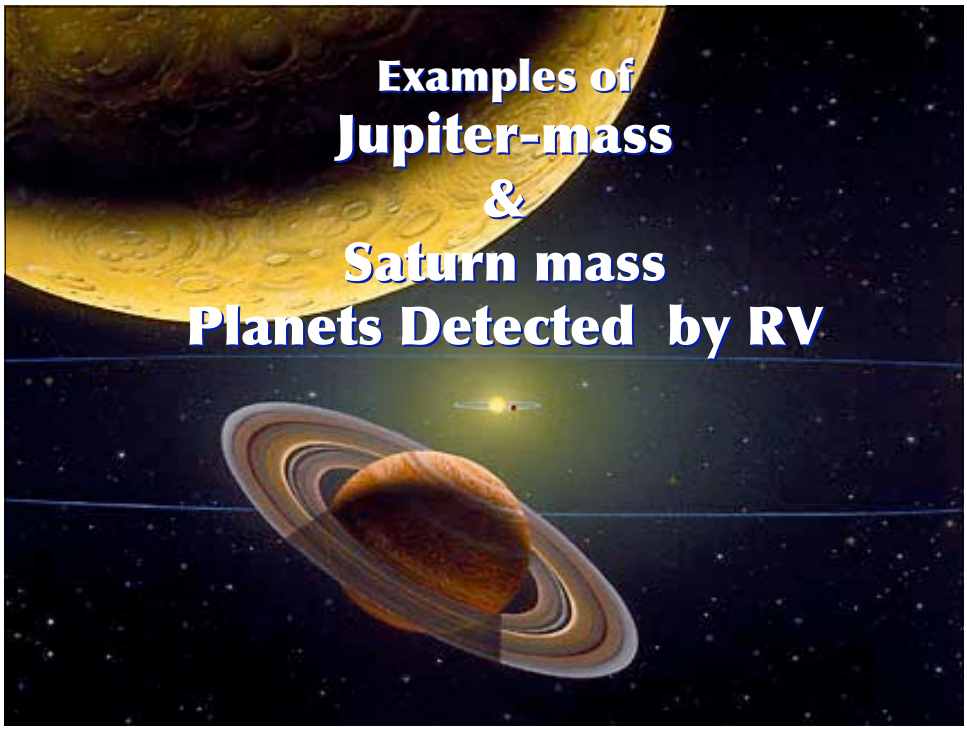

Precision: 1.5 m s⁻¹
HD 185144 (K0V)
RMS = 1.55 ms⁻¹
Velocity (m s⁻¹)
30
20
10
0
−10
−20
−30
3 Years
2004.5 2005.0 2005.5 2006.0 2006.5 2007.0 2007.5
Time (yr)


Planets or Brown Dwarfs
in Unclosed, Long-Period Orbits:
Targets for Coronagraphs

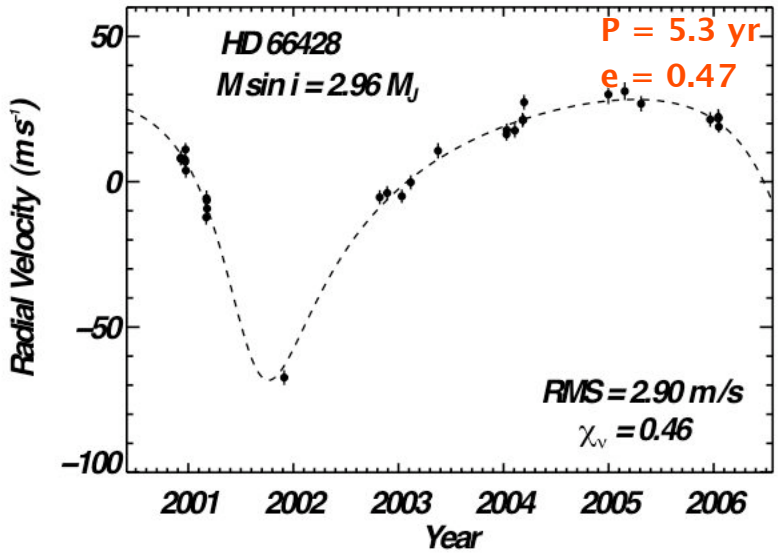

HD 104304 (G9, d=12.9 pc)
Mass = 17.20 M_JUP/sin i
P = 7.54 yr
K = 266 ms^-1
e = 0.38
Sep ~ 0.3 "
RMS = 9.76 ms^-1
Velocity (m s^-1)
400
200
0
−200
−400
2002 2003 2004 2005 2006 2007
Time (Years)


HD 111031 (G5, d=30 pc)
Mass = 2.870 M_JUP/sin i
P = 16.4 yr
K = 33.9 ms^-1
e = 0.32
Sep ~ 0.2 "
RMS = 2.65 ms^-1
Velocity (m s^-1)
60
40
20
0
−20
−40
1998 2000 2002 2004 2006 2008
Time (Years)

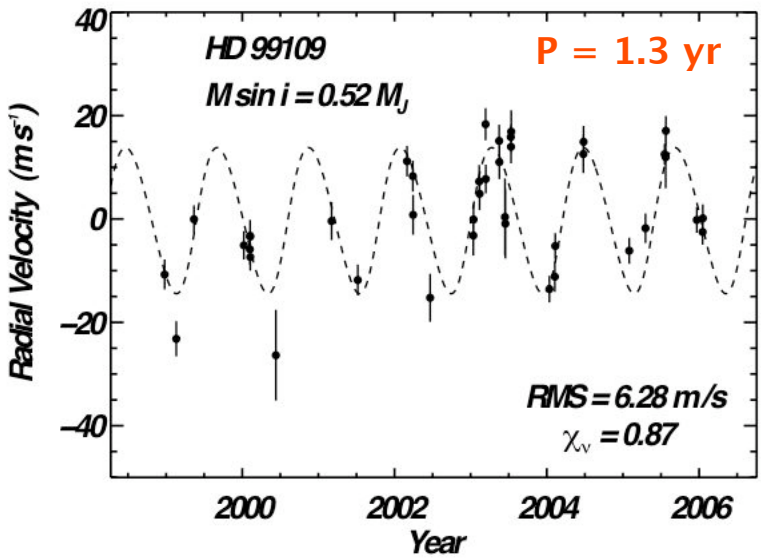

HD 129814 (G5, d=42 pc)
Mass = 43.60 M_JUP/sin i
P = 25.8 yr
K = 431 ms^-1
e = 0.33
Sep ~ 0.2”
RMS = 4.38 ms^-1
Velocity (m s^-1)
400
200
0
–200
–400
1998
2000
2002
2004
2006
Time (Years)


Examples of
Jupiter-mass
&
Saturn mass
Planets Detected by RV

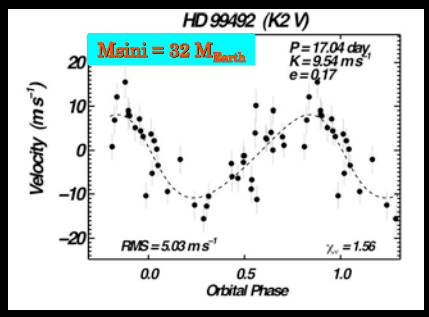
Jupiter Mass Extrasolar Planets

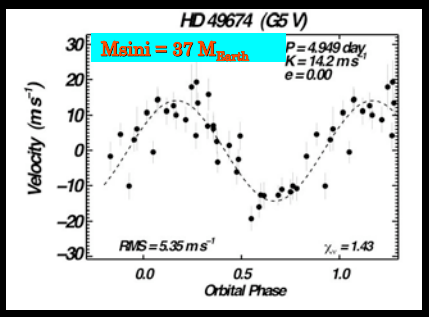


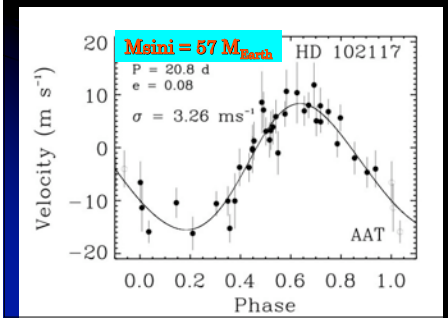
Jupiter Mass Extrasolar Planets



Sub-Saturn Masses: 30 - 100 M_{Earth}





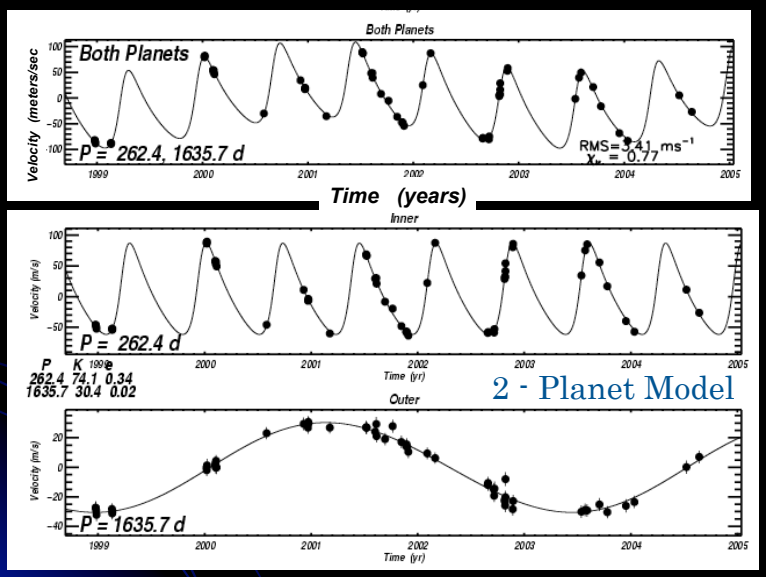


Old Doppler Precision: 3 m/s

Sub-Saturn Masses:

Detectable for P < 2 Month

HD 12661: Sun-like Star



2 - Planet Model

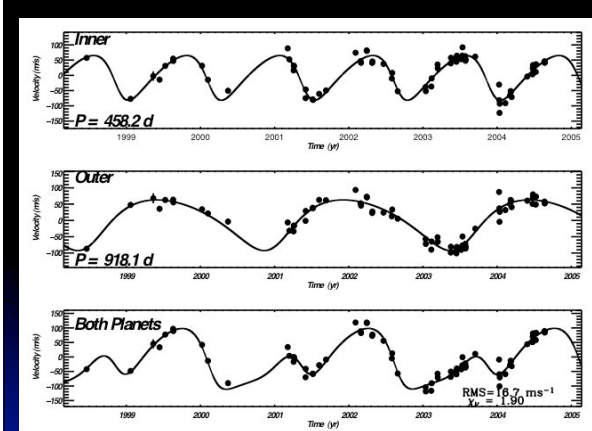
2.5 M_J
1.9 M_J

Weak Interactions

K0V, 1Gy, 16 pc

HD 128311

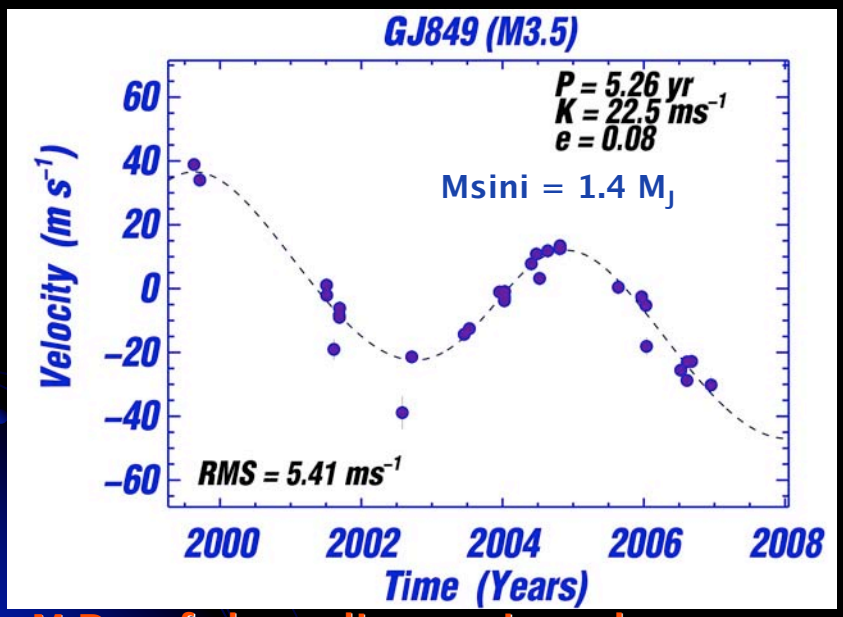
2:1 Resonance



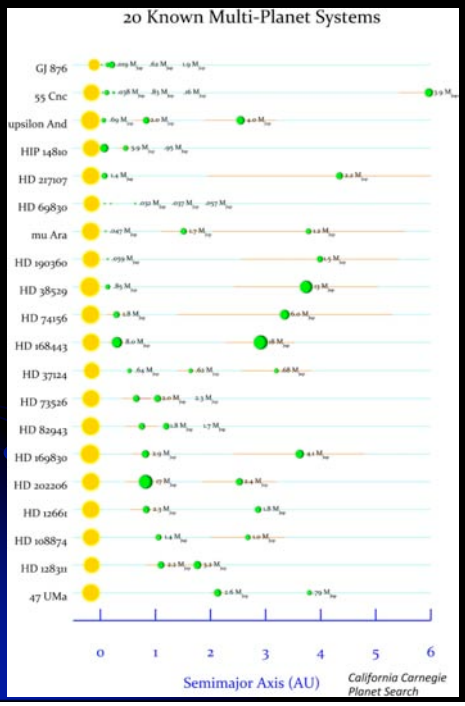
	Inner	Outer
Per (d)	458	918
Msini	2.3	3.1
ecc	0.23	0.22
ω	119	212

$P_c / P_b = 2.004$

Dynamical Resonance (Laughlin)



M Dwarfs have distant giant planets.



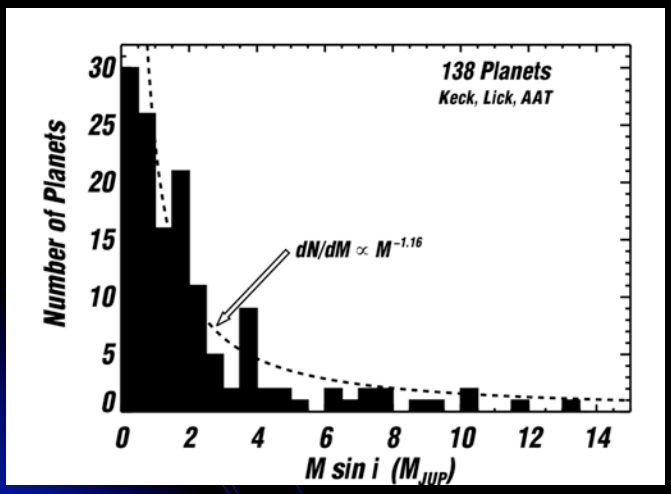
5 Mean-Motion Resonances

Implies:

- Orbital Migration
- Capture into Resonances
- Eccentrcity Pumping

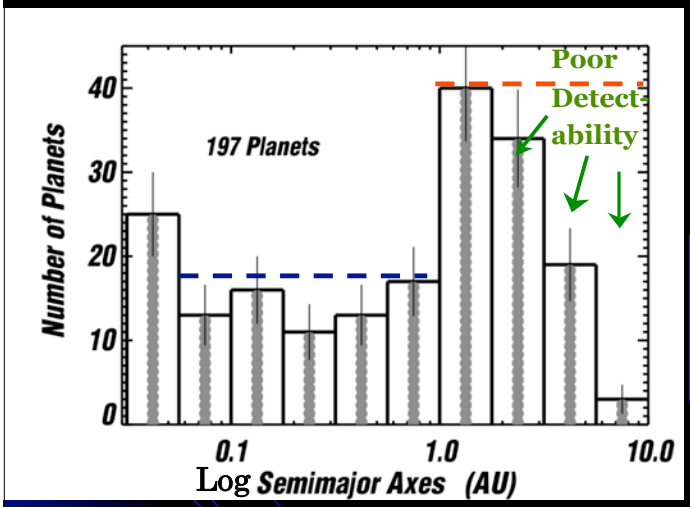
Coronagraphs can expect planets at 20 AU accompanied by inner giant planets

Giant Planets:
Mass Distribution



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

Semimajor Axis Distribution



6.5 % Occurrence

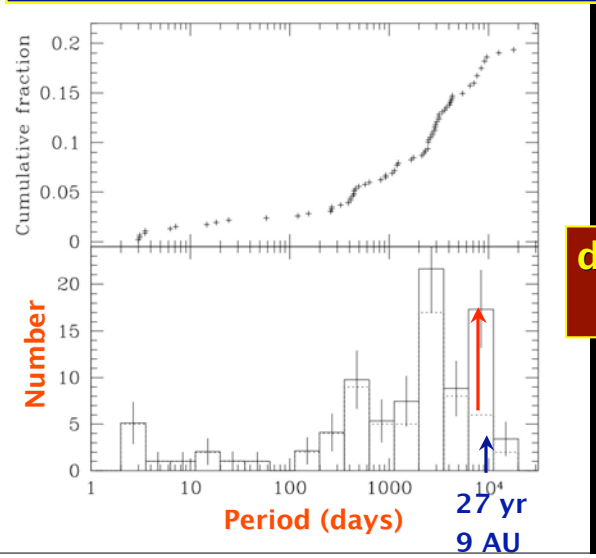
If $dN/d\log a = const$: Δ6% of stars have planets 3 - 20 AU .

12 % of stars Harbor Giant Planets

Orbital Period Distribution

Correction for Incompleteness

Cumming et al. 2007



$dN/d\log P \sim P^{\beta}$

$\beta = +0.26$

Take Home:

$dN/d\log_{10}P = 6.5\%$

Occurrence of Long Period Orbits

Cumming et al. 2007

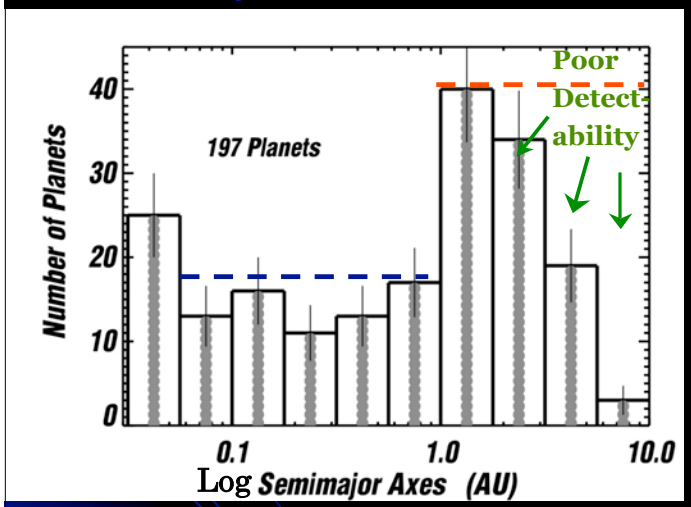
a < 3 AU	5 AU	10 AU	20 AU
8.5%	11%	14%	19%

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.

Semimajor Axis Distribution

6.5 % Occurrence



If $dN/d\log a = const$:
Δ6% of stars have planets 3 - 20 AU .

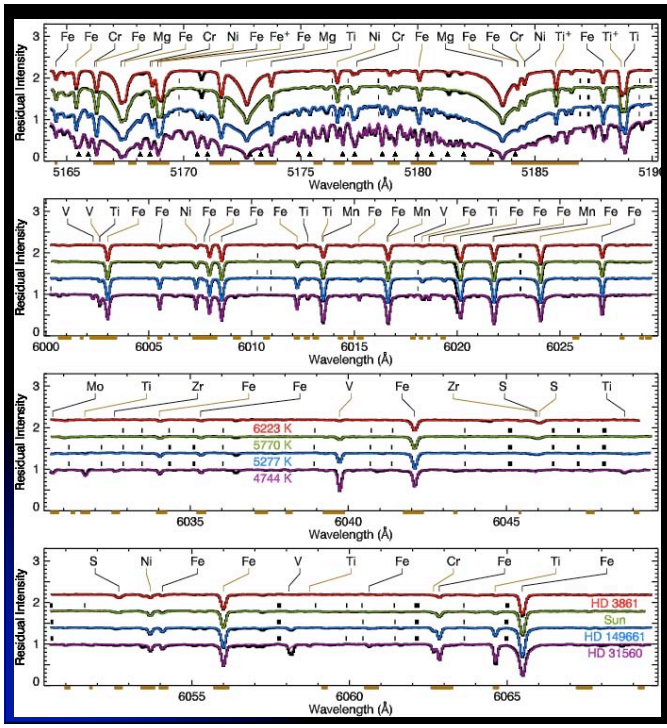
If dN/dloga = const, 6% 20-120 AU

Most Models ==>
Reservoir of Jupiters at 5-20 AU.

Few Jupiters a> 20 AU.

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

Armitage, Livio, Lubow, Pringle (2002)
Trilling, Benz, Lunine (2002)
Lin & Ida 2004
Alibert & Benz



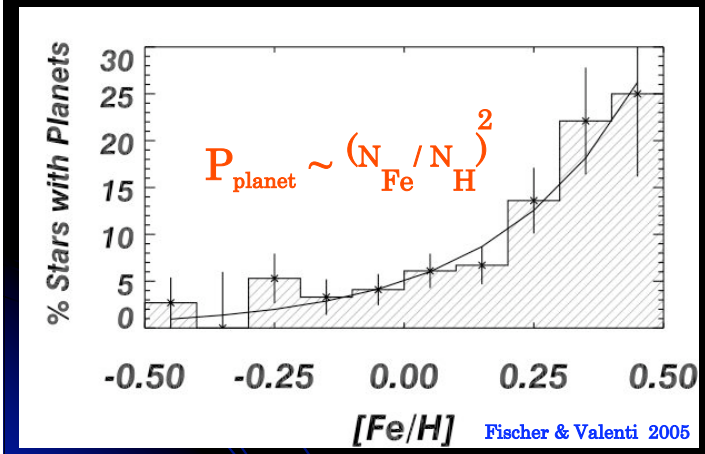
Chemical Abundances Of Stars

Fischer & Valenti

Spectral Synthesis Modeling

1) LTE radiative transfer with Kurucz model atmospheres.
2) Least-Squares fit to spectral lines.

Planet – Metalicity Correlation



Chem.Abund. Analysis of 1000 stars on planet search .

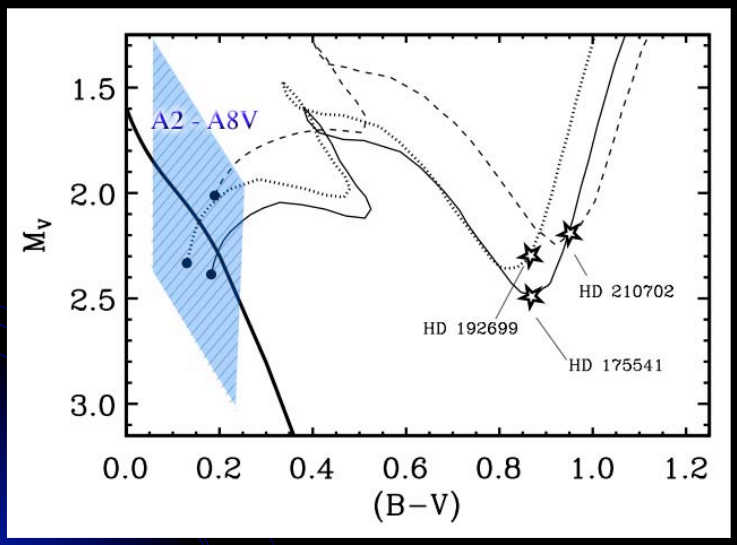
Metalicity Models:
Core-Accretion Model:
More Dust -->
Planet growth rate
Ida & Lin (2005)
Kornet et al. (2005)
Ed Thommes 2006

Previous Planet-Metallicity Corr:
G.Gonzales, N.Santos

Exoplanets as a function of Stellar Mass

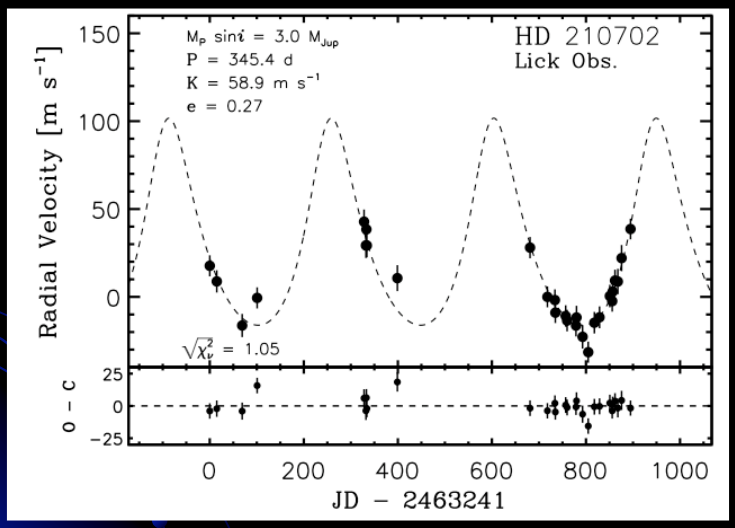
- 120 M dwarfs (0.3-0.6 M_O)
- 200 "A-type" Stars (1.5-2.0 M_O)

Retired A-Stars and Their Planets



John Johnson et al. (2007)

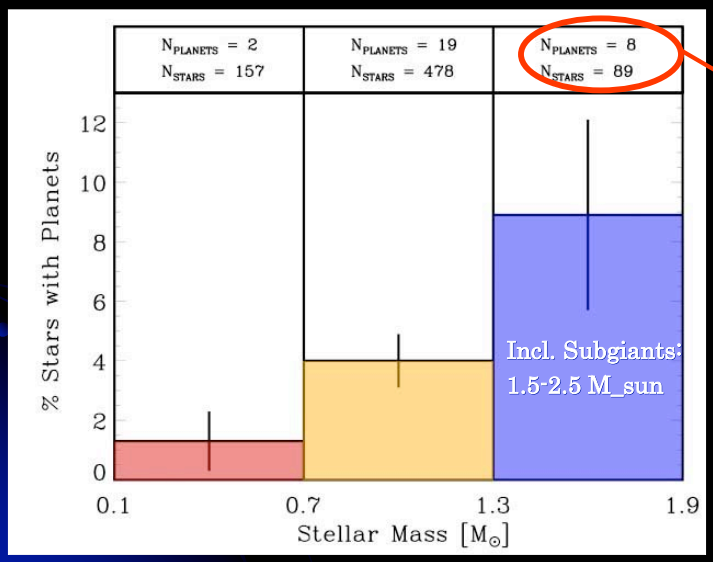
HD 210702: $M_* = 1.85\ M_\odot$



John Johnson 2007

Jupiter Occurrence vs Stellar Mass

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



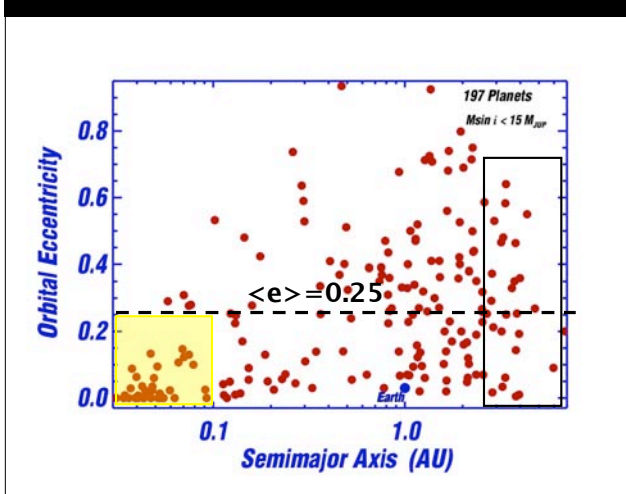
5/58 @Lick

3/31 @Keck

Beware Metallicity Effects.

John Johnson 2007

Orbital Eccentricities



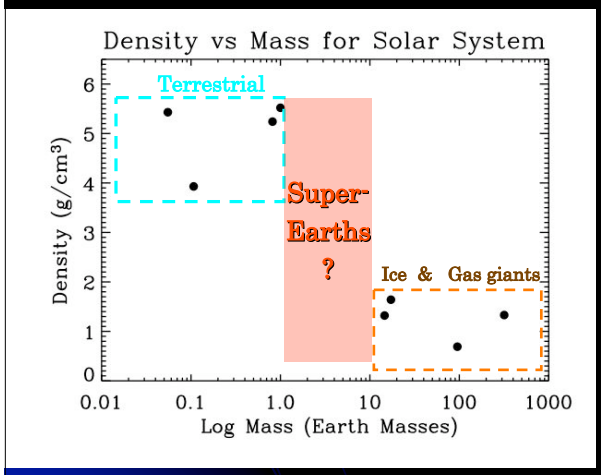
Tidal Circ.:
a < 0.1 AU

- <e> = 0.25
- Origin of eccent. *controversial .*
- *Ecc still high beyond 2.5 AU*

Origin of Eccentricities
Planet - Planet Interactions

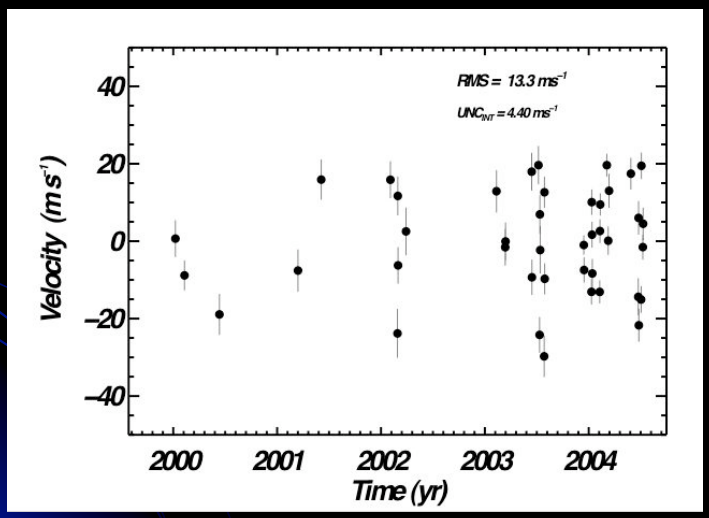
Ford & Rasio 2006

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

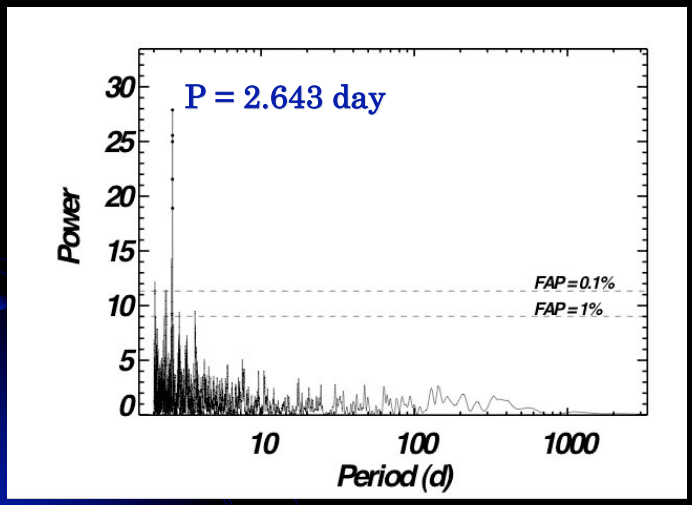


- Earth - Uranus:
  Gap in Mass: Factor 14
- Intermediate Masses:
  Do they Form?
  Or do planet embryos accrete gas ala Neptune ?
- If They Form:
  - Terr-like: CO_2 Atm. ?
  - Neptune-like H&He env ?
- Density: 1 or 5 g cm^{-3} ?

Gliese 436 (M2.5 V)

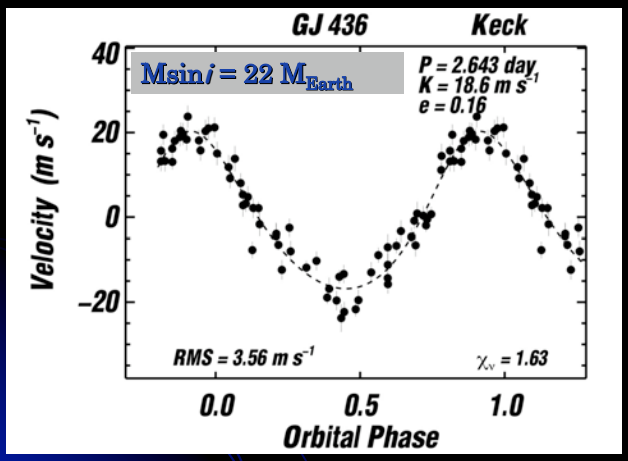


Gl 436: Periodogram



Gliese 436:

22 Earth Masses



Butler et al. 2004; Maness et al. 2007

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 ?

Gliese 436 Transits

R = 3.95 R_{Earth}

ρ = 2.0 gm/cc

photometry phase-folded using the ephemerids and period presented in Maness et al. (2007).

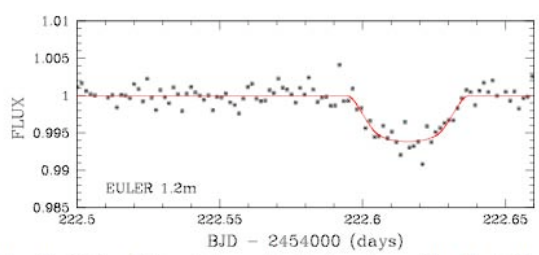
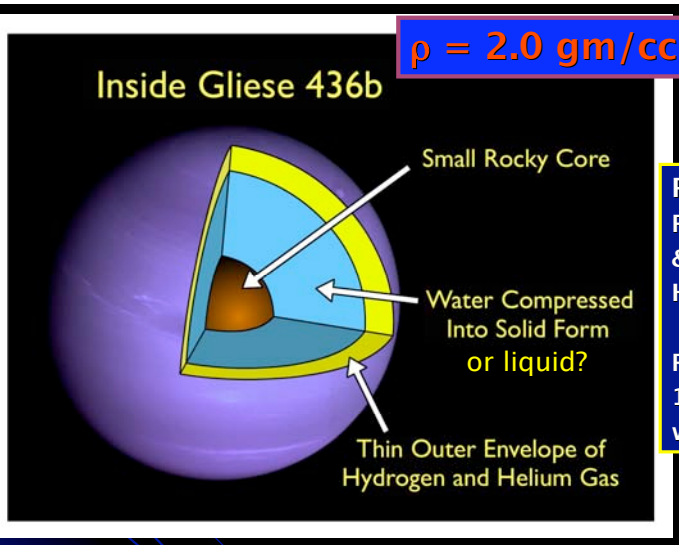


Fig. 2. Euler V-band transit photometry. The best-fit transit curve is superimposed in red.

Gillon et al 2007



ρ = 2.0 gm/cc

Possible:
Rocky core
&
H/He Env.

Requires unlikely
17 M_Earth of rock
within 1 AU.

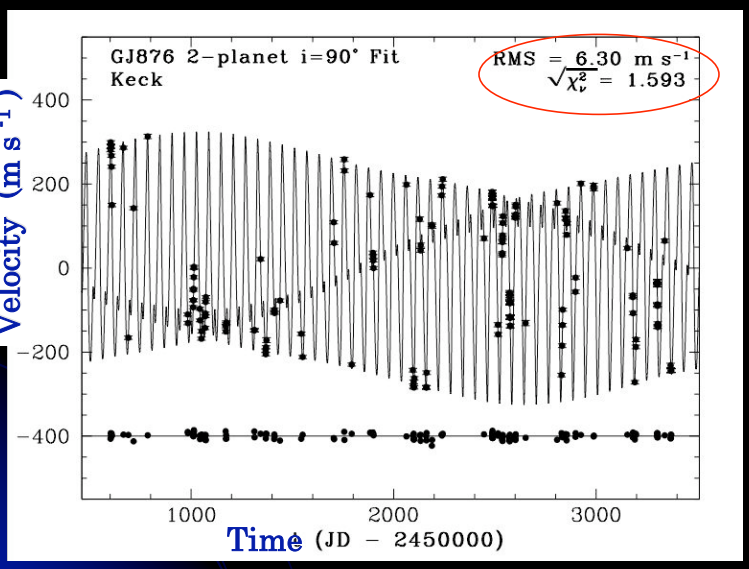
Model from Fortney, Marley, & Jones 2007

"It seems likely that planets with masses within an order of magnitude of the Earth's mass will be composed primary of …ices, rocks, and iron."

Gliese 876 (M3V)

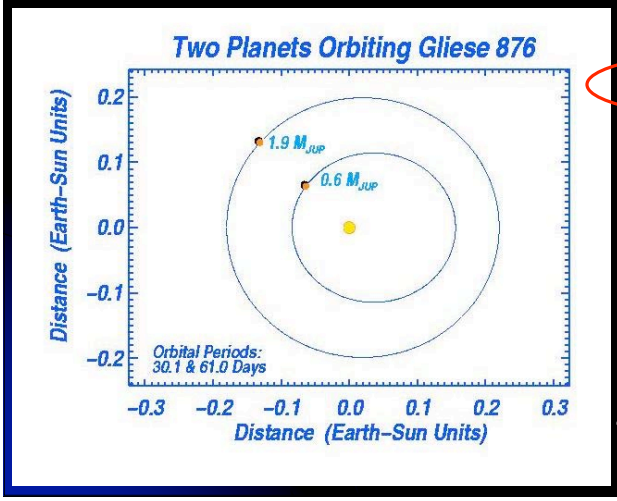
- Star Mass = 0.32 M_{sun}
- d = 4 pc
- Two Jupiters in 2:1 res.

Gliese 876: 2-Planet Fit



GL 876

2:1 Mean-Motion Resonance & Apsidal Lock

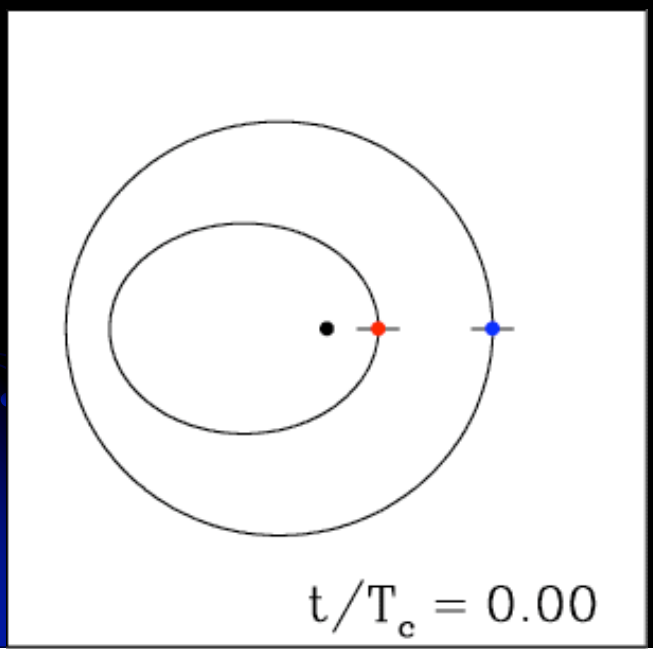


	Inner	Outer
P	30.1	61.0 d
Msini	0.56	1.89 M_J
e	0.27	0.10
ω	330	333°

Resonance Work:

- Laughlin & Chambers
- Lissauer & Rivera
- Man Hoi Lee & S.Peale

Gliese 876



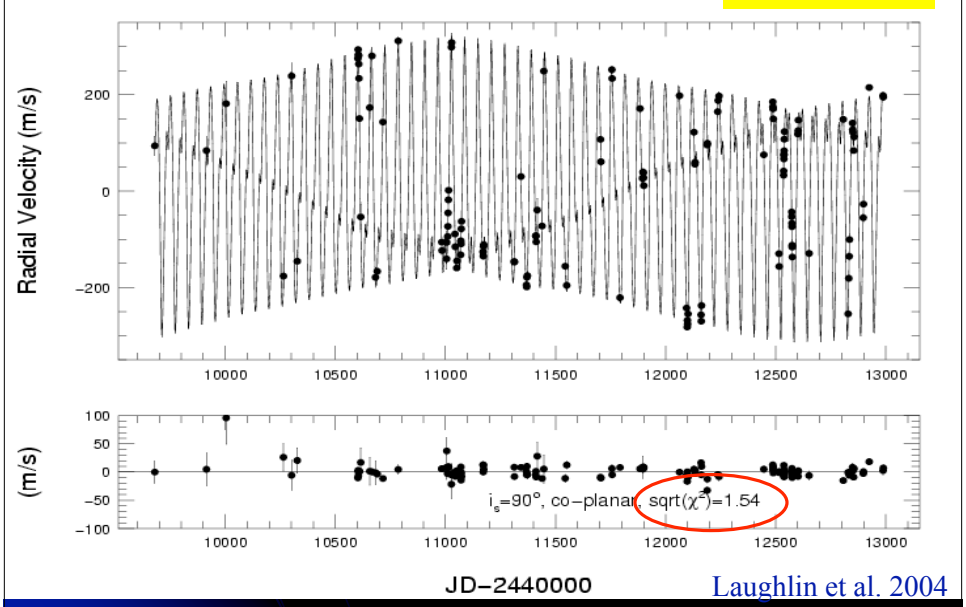
- 2:1 Mean Motion Resonance

Precession Period: 9 yr

Man Hoi Lee

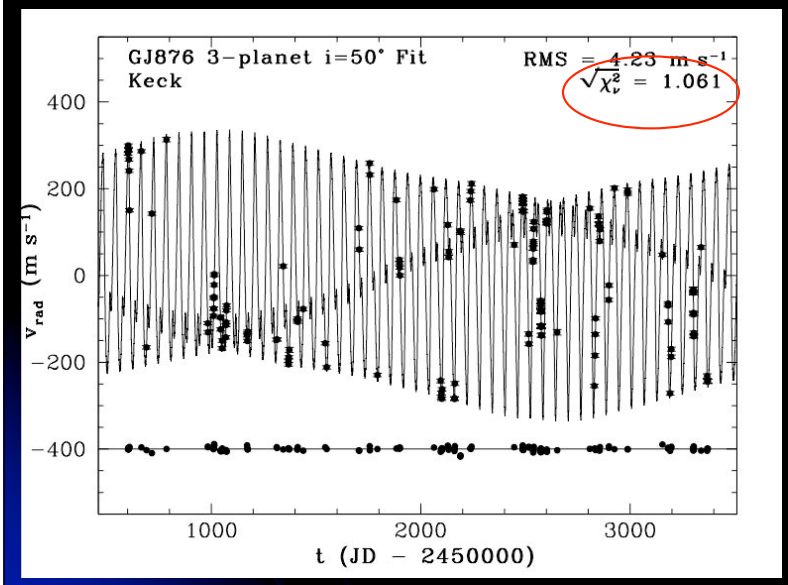
GJ 876: Velocities

Two-Planet Model



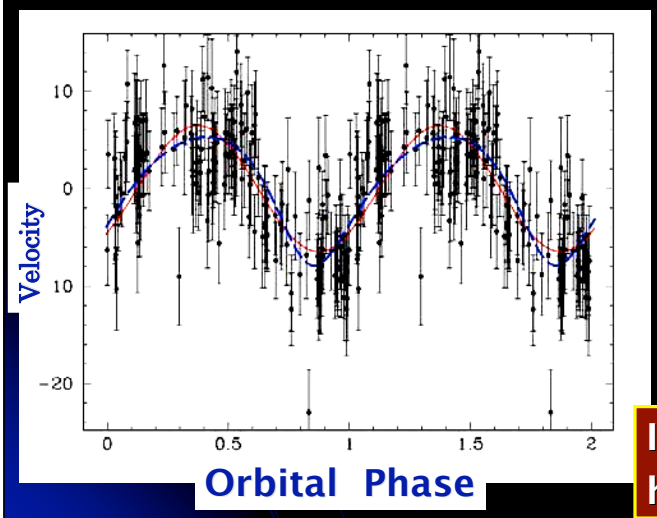
Laughlin et al. 2004

3-Planet Fit



Rivera & Lissauer

Velocity Residuals to 2-Planet fit



Period = 1.94 d

M sini = 5.9 M_{Earth}

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

Inward of habitable zone

Astronomy & Astrophysics manuscript no.
(DOI: will be inserted by hand later)

April 29, 2007

The HARPS search for southern extra-solar planets*

XI. Super-Earths (5 & 8 $M_\oplus$) in a 3-planet system

S. Udry[1], X. Bonfils[2], X. Delfosse[3], T. Forveille[3], M. Mayor[1], C. Perrier[3], F. Bouchy[4], C. Lovis[1], F. Pepe[1], D. Queloz[1], and J.-L. Bertaux[5]

[1] Observatoire de Genève, Université de Genève, 51 ch. des Maillettes, 1290 Sauverny, Switzerland
e-mail: stephane.udry@obs.unige.ch
[2] Centro de Astronomia e Astrofísica da Universidade de Lisboa, Tapada da Ajuda, 1349-018 Lisboa, Portugal
[3] Laboratoire d'Astrophysique, Observatoire de Grenoble, Université J. Fourier, BP 53, F-38041 Grenoble, Cedex 9, France
[4] Institut d'Astrophysique de Paris, CNRS, Université Pierre et Marie Curie, 98bis Bd Arago, 75014 Paris, France
[5] Service d'Aéronomie du CNRS/IPSL, Université de Versailles Saint-Quentin, BP3, 91371 Verrières-le-Buisson, France

Received ; accepted To be inserted later

Abstract. This Letter reports on the detection of two super-Earth planets in the Gl 581 system, already known to harbour a hot Neptune. One of the planets has a mass of 5 $M_\oplus$ and resides at the "warm" edge of the habitable zone of the star. It is thus the known exoplanet which most resembles our own Earth. The other planet has a 7.7 $M_\oplus$ mass and orbits at 0.25 AU from the star, close to the "cold" edge of the habitable zone. These two new light planets around an M3 dwarf further confirm the formerly tentative statistical trend for i) many more very low-mass planets being found around M dwarfs than around solar-type stars and ii) low-mass planets outnumbering Jovian planets around M dwarfs.

Key words. stars: individual: Gl 581, stars: planetary systems – 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 solar-type stars. In particular, Earth-mass planets

in Neptune-mass planet. The minimum mass of the 2nd new planet is 5.03 terrestrial mass, the lowest for any exoplanet to date, close to the 5.5 $M_\oplus$ of the microlensing candidate OGLE-2005-BLG-390Lb (Beaulieu et al. 2006) found at a large separation from another M dwarf. It resides at the inner edge of the habitable zone of Gl 581. The 3rd planet, at 0.25 AU from the star, is also in the super-Earth category (7.7 $M_\oplus$), and is situated close to the outer edge of the habitable zone of the system.

Gliese 581

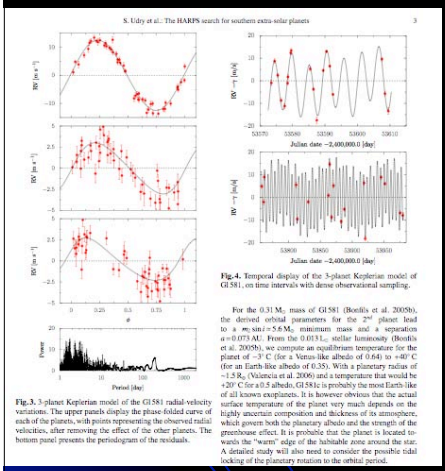


Fig. 3. 3-planet Keplerian model of the Gl 581 radial-velocity variations. The upper panels display the phase-folded curve of each of the planets, with points representing the observed radial velocities, after removing the effect of the other planets. The bottom panel presents the periodogram of the residuals.

Fig. 4. Temporal display of the 3-planet Keplerian model of Gl 581, on time intervals with dense observational sampling.

For the 0.31 $M_\oplus$ mass of Gl 581 (Bonfils et al. 2005b), the derived orbital parameters for the 2nd planet lead to a $m_2 \sin i = 5.6\,M_\oplus$ minimum mass and a separation $a = 0.073$ AU. From the $0.013\,L_\odot$ stellar luminosity (Bonfils et al. 2005b), we compute an equilibrium temperature for the planet of −3° C (for a Venus-like albedo of 0.64) to +40° C (for an Earth-like albedo of 0.35). With a planetary radius of $\sim 1.5\,R_\oplus$ (Valencia et al. 2006) and a temperature that would be +20° C for a 0.5 albedo, Gl 581c is probably the most Earth-like of all known exoplanets. It is however obvious that the actual surface temperature of the planet very much depends on the highly uncertain composition and thickness of its atmosphere, which govern both the planetary albedo and the strength of the greenhouse effect. It is probable that the planet is located towards the "warm" edge of the habitable zone around the star. A detailed study will also need to consider the possible tidal locking of the planetary rotation to the orbital period.

	Orbit Radius(AU)	Min.Mass (Earths)	Likely Mass (x 4/π) (Earths)	
b	0.041	15.2	19	
c	0.073	5.0	6.4	"T = 0-40 C"
d	0.25	8.2	10.4	

Planet "c" :

1) Actual Habitable Zone: 0.10–0.20 AU

Efficient IR opacity -> heating in any atmosphere (Sasselov, Selsis, Kasting, Seager, Bloh, Cuntz, 2007)

(Potsdam preprint)

2) Mass: Arguably an Ice Giant:

~ Gliese 436 b, Uranus, Neptune

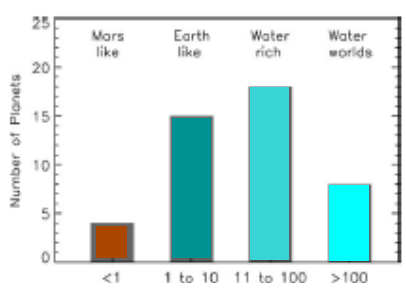
See Xavier Bonfils talk.

In a protoplanetary disk,
if 6 M_{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 Content (Earth Oceans)

Fig. 9. Histogram of the water content of 45 planets with 0.8 AU < a < 1.5 AU which formed in 44 simulations. See text for discussion.

N-Body Planet Growth with Water Delivery
Raymond, Quinn, Lunine 2004

- Water Delivery: Comets & hydrated asteroids
- H_2O content vs r_{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"

Super Earths

Formation *beyond* 2 AU

Leger et al. 2004

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

Phase Diagram of Water

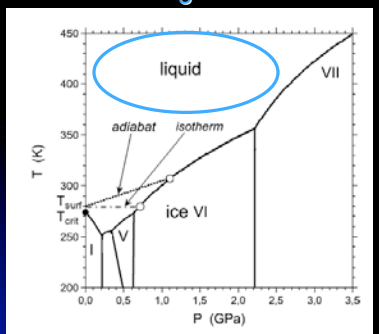


Fig. 2. Phase diagram for water (full lines). The dotted (dashed-dotted) line describes the temperature adiabatic (isothermal) profile in the ocean that results from a given surface value (here, 280 K = 7 °C). A

Structure

- Solve Interior Eqns.

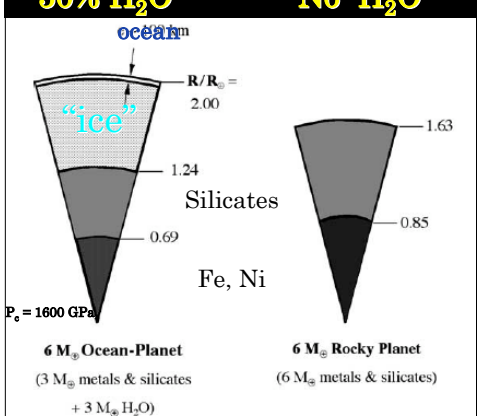
  Include EOS of water + Rock mantle + Fe core
- Water is *liquid* at high pressure (~Europa) .

WaterWorlds

10 - 50% H_2O

6 M_{Earth} Planets:

50% H_2O No H_2O



$\rho = 4.3$ g cm^{-3} $\rho = 7.7$ g cm^{-3}

- H_2O Atmosphere +
- H_2O Ocean +
- Ice Envelope (ala Neptune)

- Lower Density than rocky planets
- Distinguish water worlds from rocky worlds:

  Radial velocity and transit ---> M , R .

Leger 2004, Raymond 2005

Detecting Rocky Planets by Doppler Measurements of Stars

Star's Wobble Velocity:

$K = 0.1$ m/s $[M_{pl}/M_{star}\ 1/a_{AU}^{1/2}]$ (M_{pl} in M_E)

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 Metalicity & 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

→