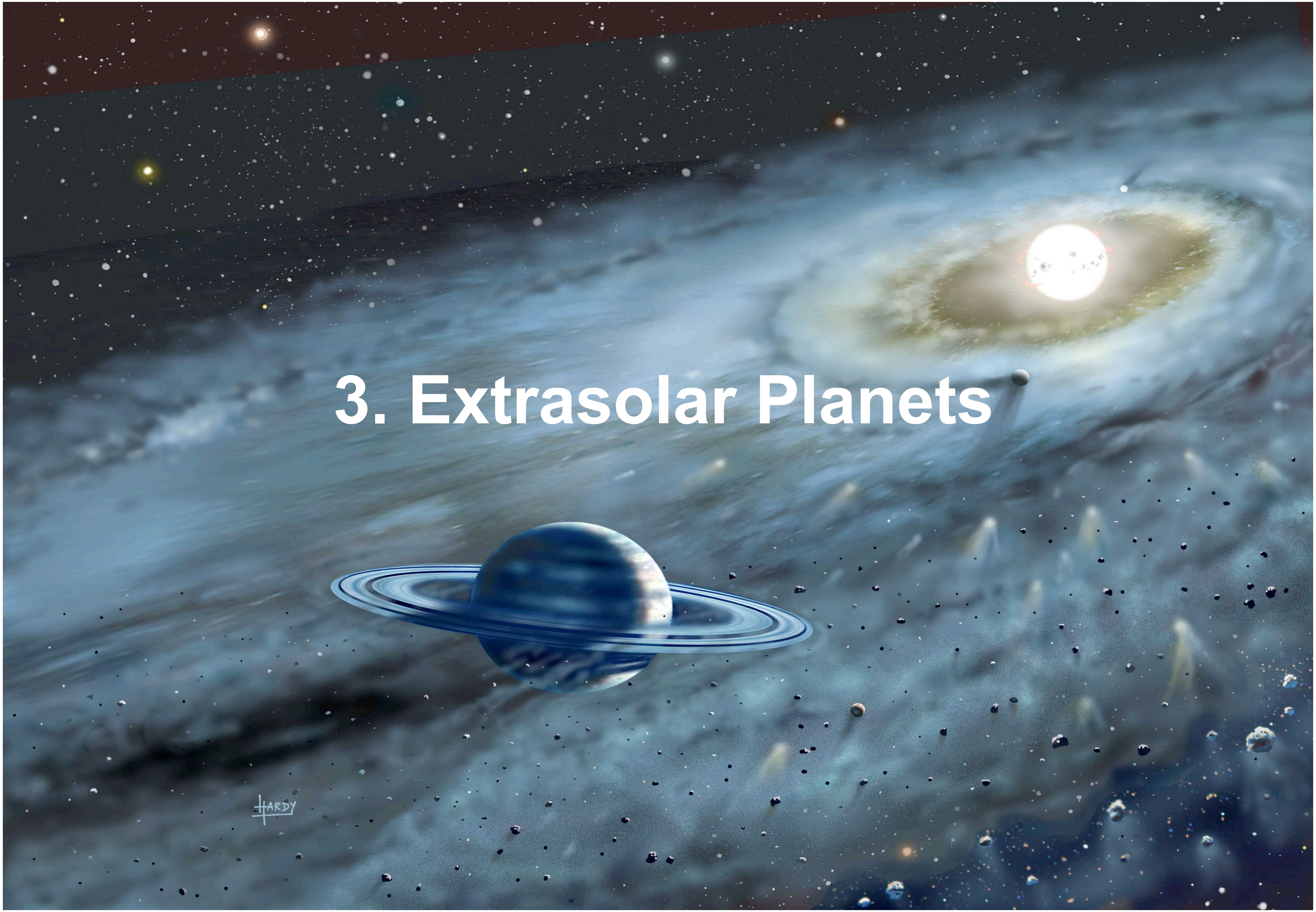
3. Extrasolar Planets

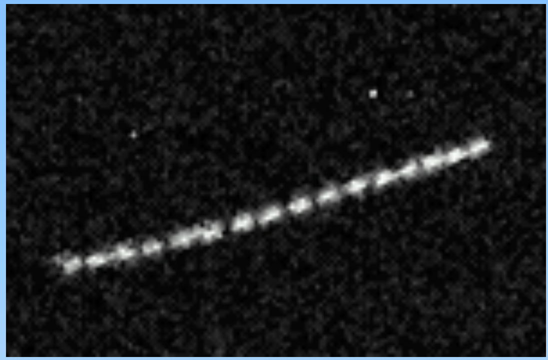


How planets were discovered in the solar system

Many are bright enough to see with the naked eye!

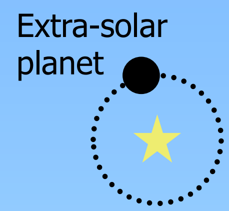
More distant planets are fainter (scattered light flux $\propto a_{pl}^{-4}$) and were discovered by imaging the sky at different times and looking for fast-moving things which must be relatively nearby (Kuiper belt objects and asteroids etc are still discovered in this way) but some (e.g., Neptune) were predicted based on perturbations to the orbit of known planets

Problem for detecting planets is that there is a lot of area of sky the planets could be hiding in, so narrow searches to ecliptic planet (although tenth planet has $i=45^0$) and use knowledge of dynamics to predict planet locations

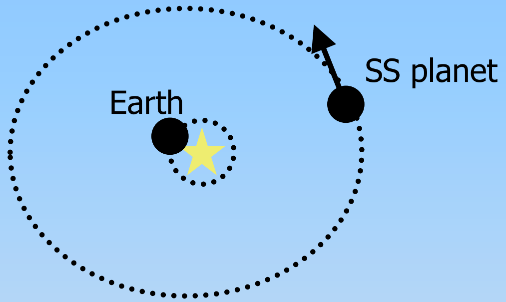


People are still searching for planet X in the solar system (e.g., Gaudi & Bloom 2005 say Gaia will detect $1M_J$ out to 2000AU)

Can we do the same thing in extra-solar systems?

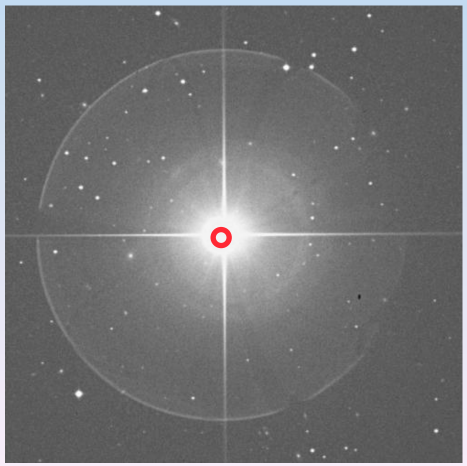


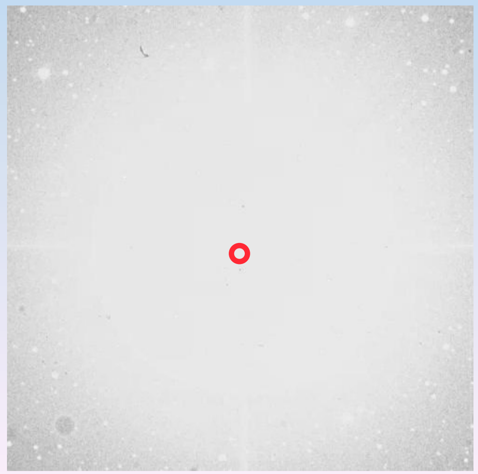
Not quite so easily!



The geometry of the problem is different, which means that:

• you don’t get a continuous motion across the sky
• although we have narrowed down the region where the planet can be
• but the planet is very far away and so it is faint, scattered light flux $\propto d_*^{-2} a_{pl}^{-2}$ where d_* is measured in pc (1pc=206,265AU)
• which is compounded by the fact that it is close to a very bright star





So how do we detect extrasolar planets?

Mostly using indirect detection techniques:

Effect on motion of parent star
- Astrometric wobble
- Timing shifts
- Doppler wobble method

Effect on flux we detect from parent star
- Planetary transits
- Gravitational microlensing (rather flux from another star)

Direct detection techniques are now possible
- Direct imaging

New techniques are also being developed
- Disk structures

Basics of effect on stellar motion

Two body orbital motion in the barycentric reference frame shows that both bodies orbit the centre of mass on ellipses

The centre of mass of a star+planet system moves through the galaxy on its own galactic orbit which means that the star has perturbations to that motion due to the planet

That perturbation has a period

$t_{per} = a_{pl}^{1.5}(M_* + M_{pl})^{-0.5}$

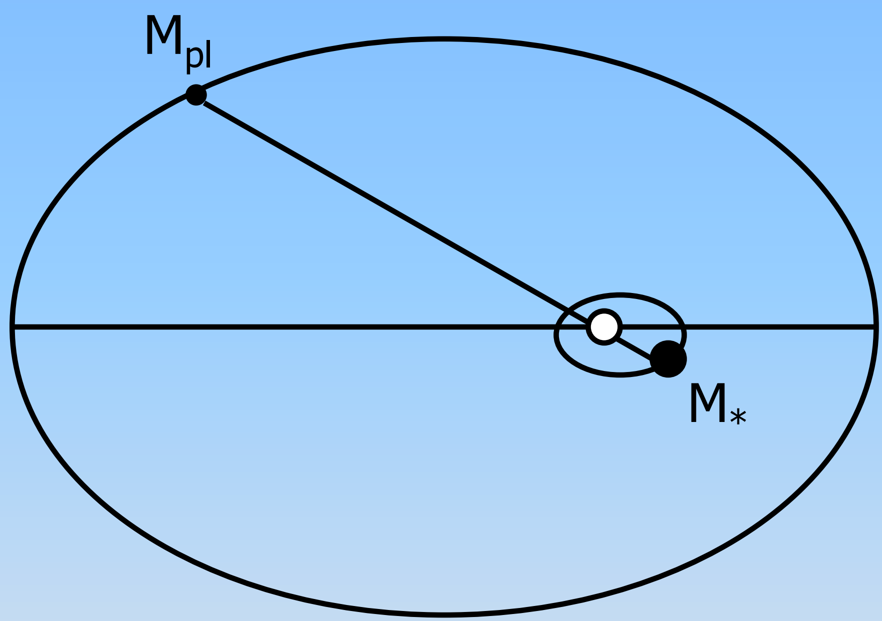
a size scale

$a_* = a_{pl}\,[M_{pl}/(M_* + M_{pl})]$

And velocity

$v_* = 30\,[(M_* + M_{pl})/a_{pl}]^{0.5}\,[M_{pl}/(M_* + M_{pl})]$ km/s

with deviations in size and velocity due to orbital eccentricity

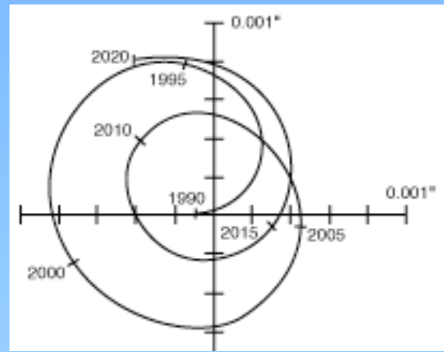


Motion with multiple bodies is also easy to work out, since it is just involves referring the orbits to the barycentric frame

Methods using motion of parent star

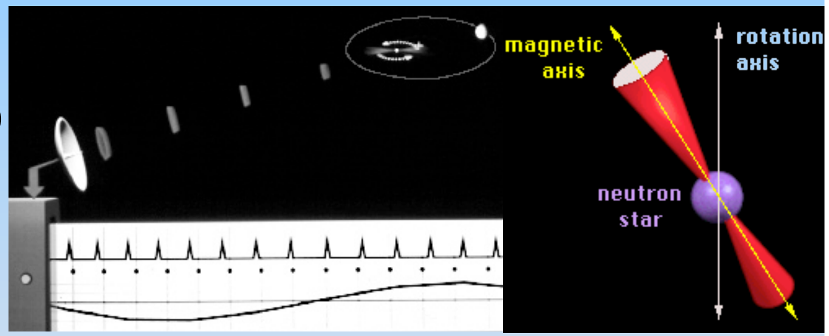
Astrometric wobble = in plane of sky

Involves precise astrometry: angular scale is $2\text{x}10^{-3}(a_{pl}/d_*)(M_{pl}/M_J)(M_{sun}/M_*)$ arcsec, so Jupiter around $1M_{sun}$ at 10 pc is 10^{-3} arcsec



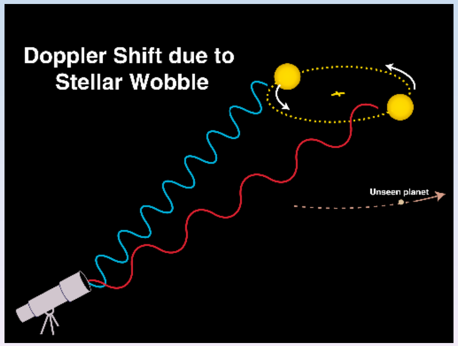
Timing shifts = using stars with regular pulses

Requires stars to be precise clocks: ms radio pulsars are ideal for this study, since $\Delta t = 3a_{pl}(M_{pl}/M_{earth})(M_{sun}/M_{star})$ ms, so Earth around $1M_{sun}$ would give a 3 ms shift



Doppler wobble method = out of sky plane

Involves precise measurement of stellar radial velocity: semiamplitude is $30a_{pl}^{-0.5}(M_{pl}/M_J)(M_*/M_{sun})^{-0.5}$ m/s, so Jupiter around $1M_{sun}$ is 13 m/s



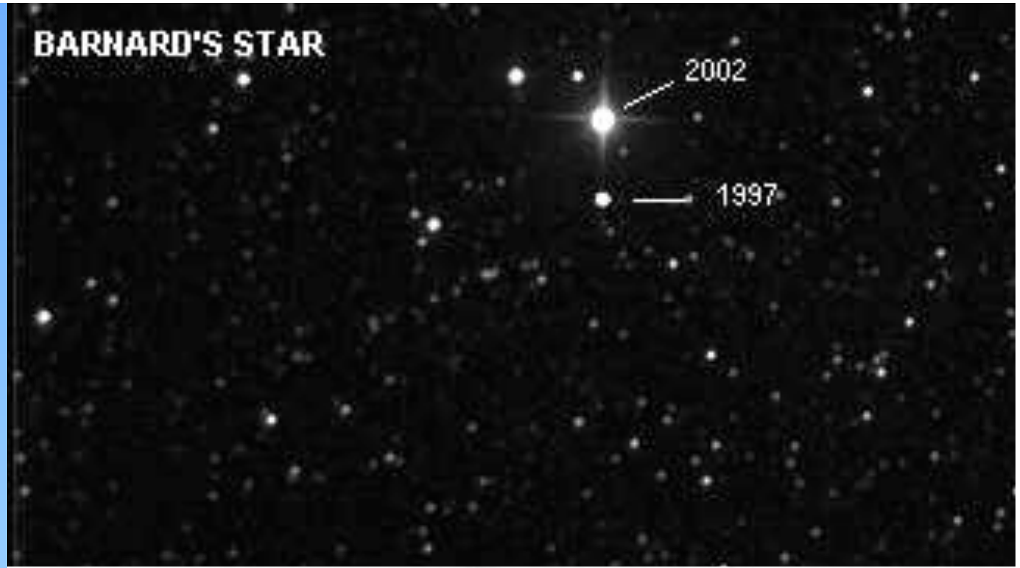
First claimed detection of extrasolar planet invoked astrometric wobble

The star: Barnard's star (M3.8Ve, 0.17M_{sun}, 0.0035L_{sun}) is old at ~11 Gyr (sub-solar metallicity, high space motion=11"/yr) and nearby 1.8pc

The planets: van de Kamp (1982) proposed 2 planets of 0.5 and 0.7M_J in orbits of 12 and 20 years

Not there: Benedict et al. (1999); Schroeder et al. (2000), Kurster et al. (2003) set more stringent limits

Original claims may be due to fact that telescope was taken out of its mount in 1949 for cleaning



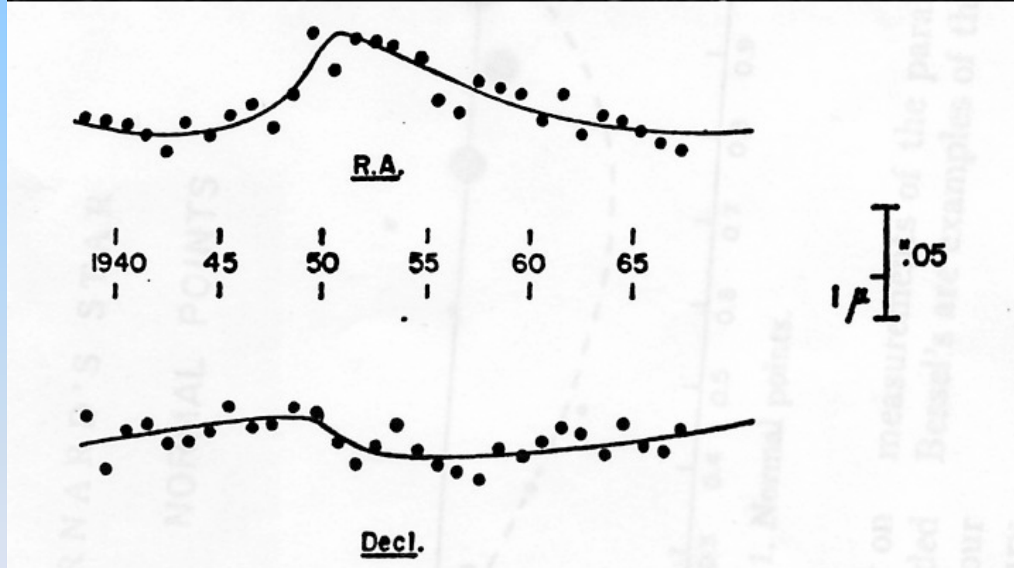
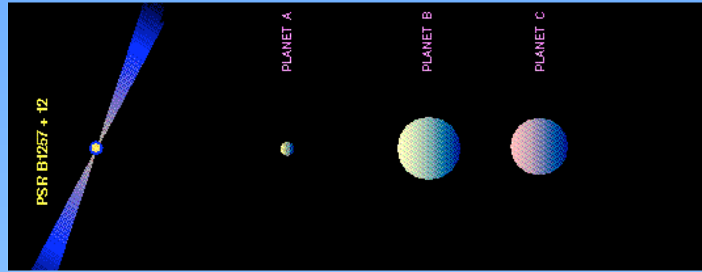


FIG. 1. Barnard's star: Yearly means, averaging 100 plates and weight 68; time–displacement curves for $P=25$ yr, $e=0.75$, $T=1950$.

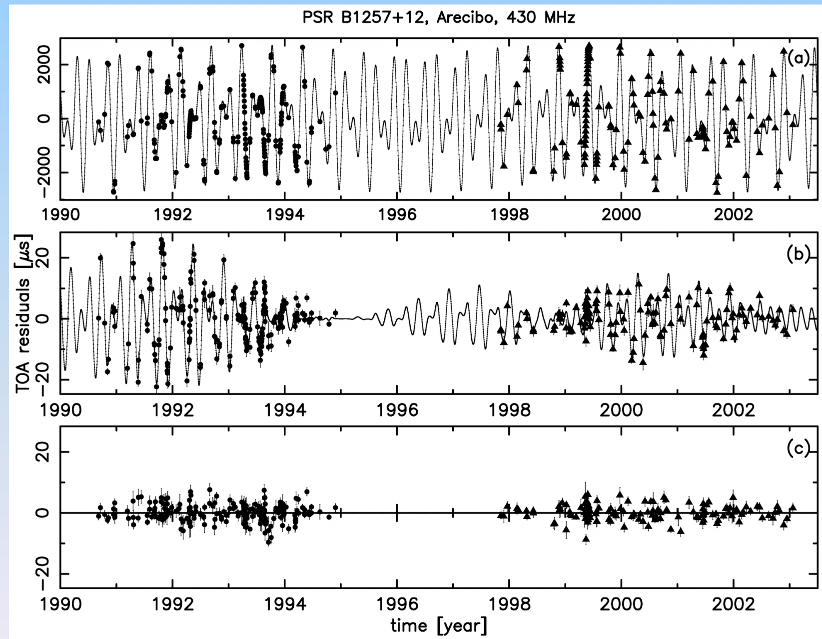
Pulsar Planets



First extrasolar planets were detected using the timing method with the 305m Arecibo telescope around 6.2 ms pulsar PSR B1257+12 (Wolszczan & Frail 1992)

	a, AU	M, M_{earth}	I	e
A	0.19	0.02	-	0
B	0.36	4.3	53^0	0.019
C	0.47	3.9	47^0	0.025

The planets are small, coplanar, low eccentricity (Konacki & Wolszczan 2003); B and C are near 3:2 resonance

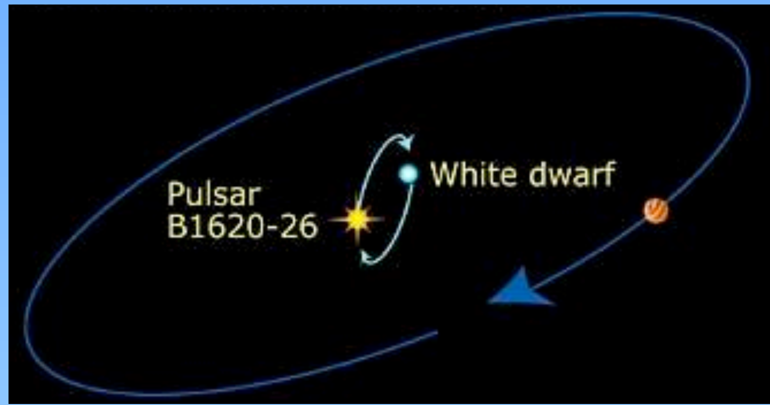


Mutual gravitational interactions between B and C (Malhotra 1992) detected meaning that orbital planes and masses derived

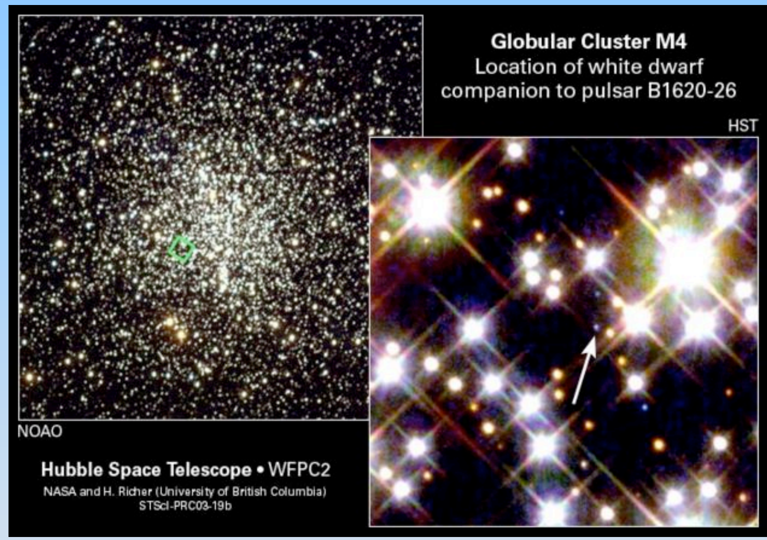
Possible fourth planet or asteroid belt beyond C (Wolszczan et al. 2000)

More pulsar planets?

Pulsar planets appear to be rare, since only one other is known to exist, around B1620-26, but in quite different circumstances to B1257+12



The system is in the globular cluster M4, and involves a $1.4M_{sun}$ neutron star orbited by a $0.34M_{sun}$ white dwarf (a=0.8AU, e=0.025), and a $7M_J$ planet (a=60 AU, e=0.45) (Thorsett et al. 1999; Ford et al. 2000)



While the neutron star is 12.7 Gyr old, the white dwarf is just 480 Myr old (Sigurdson et al. 2003)

No possibility of life on pulsar planets because of the intense radiation of the pulsar, but their origin is subject of much speculation:
• PSR B1257+12 planets formed in proto-pulsar disk
• PSR B1620-26 planet was captured in a dynamical exchange reaction in core of the cluster (indicating that planets can form in low metallicity environment)

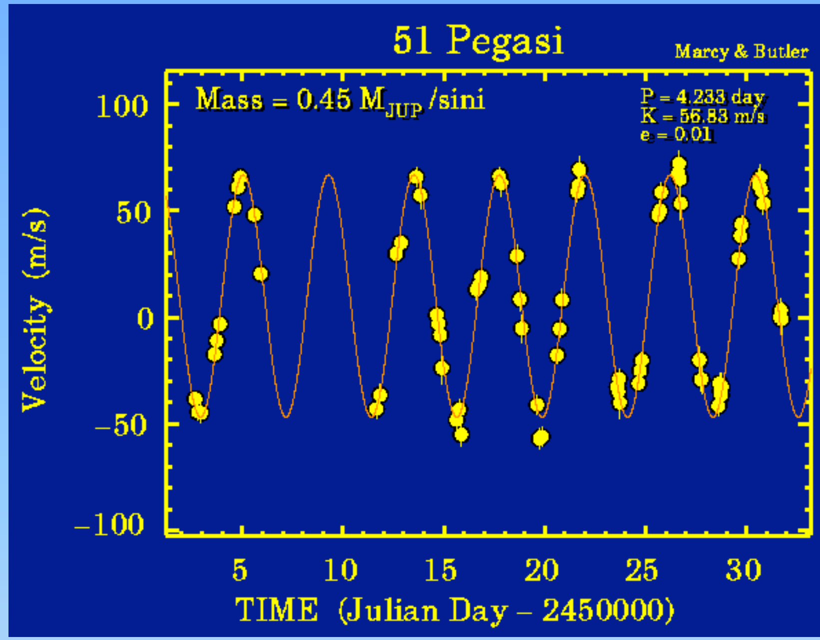
Doppler Wobble Planets

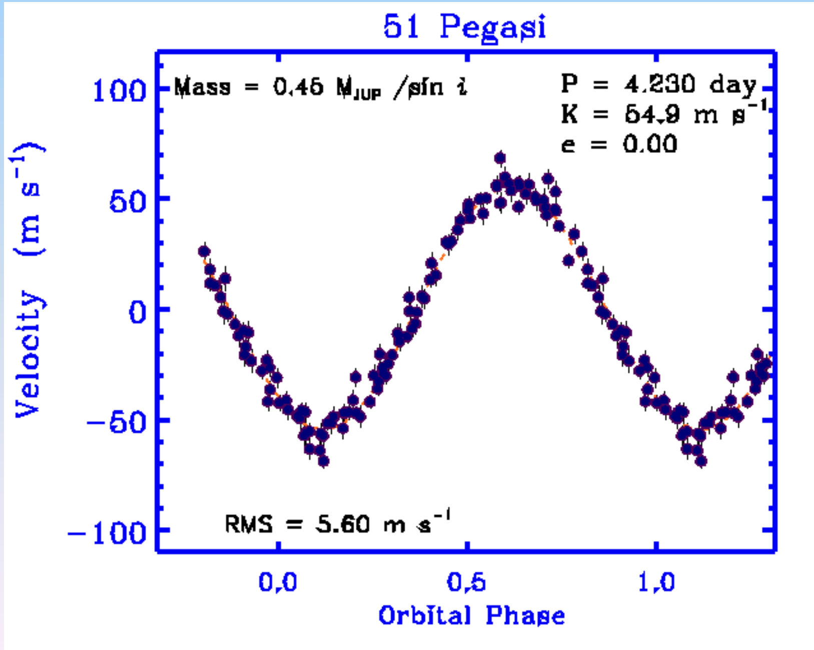
The first extrasolar planet around a normal main sequence star was found using the doppler wobble method around 51 Peg (Mayor & Queloz 1995) and later confirmed (Marcy & Butler 1997)

The star is a G2 at 15.3 pc, and its planet has a mass of at least 0.45 $M_{jupiter}$ (higher if orbit not edge-on)

Planet orbits at 0.05 AU from the star with a near circular orbit (e<0.01)

First **HOT JUPITER**



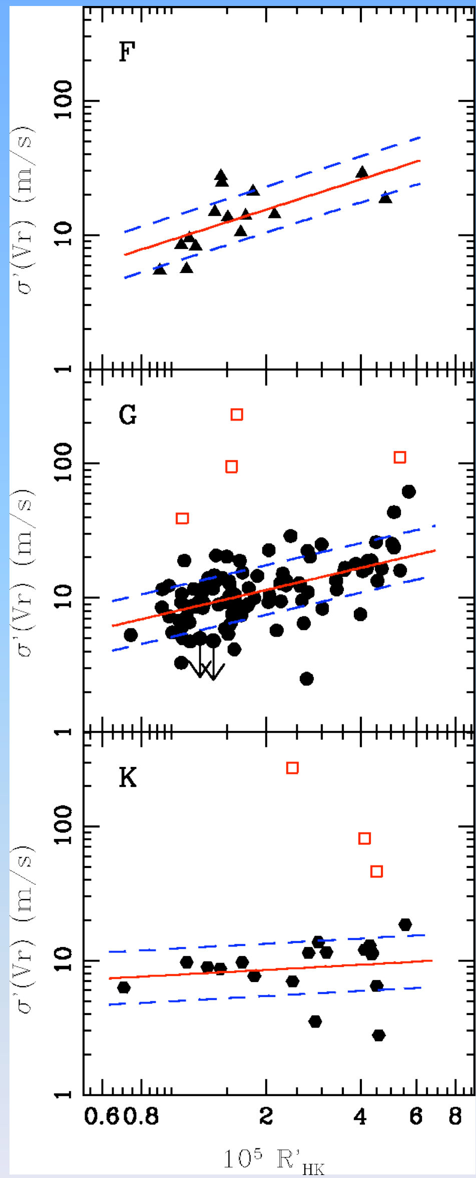


Doppler Wobble Technique

There are three main groups doing long term monitoring:
• California/Carnegie (Marcy et al.)
exoplanets.org
• Geneva group (Mayor et al.)
obswww.unige.ch/~udry/planet/planet.html
• Anglo-Australian (Butler et al.)
www.aao.gov.au/local/www/cgt/planet/aat.html
See also www.obspm.fr/planets

But there are many other groups starting (e.g., Ge et al.), and smaller projects are possible by applying for time

In general need to know about stars, since these provide major pitfalls:
• rotational velocity broadens lines, so need vsini
• chromospheric activity/star spots/active regions on stellar surface gives large jitter (e.g., Santos et al. 2000)
• potential radial oscillations mimic planet (Gray et al. 1997)
• different spectral types have fewer lines



Doppler Wobble Planet Summary

To date ~309 planets have been discovered using this method

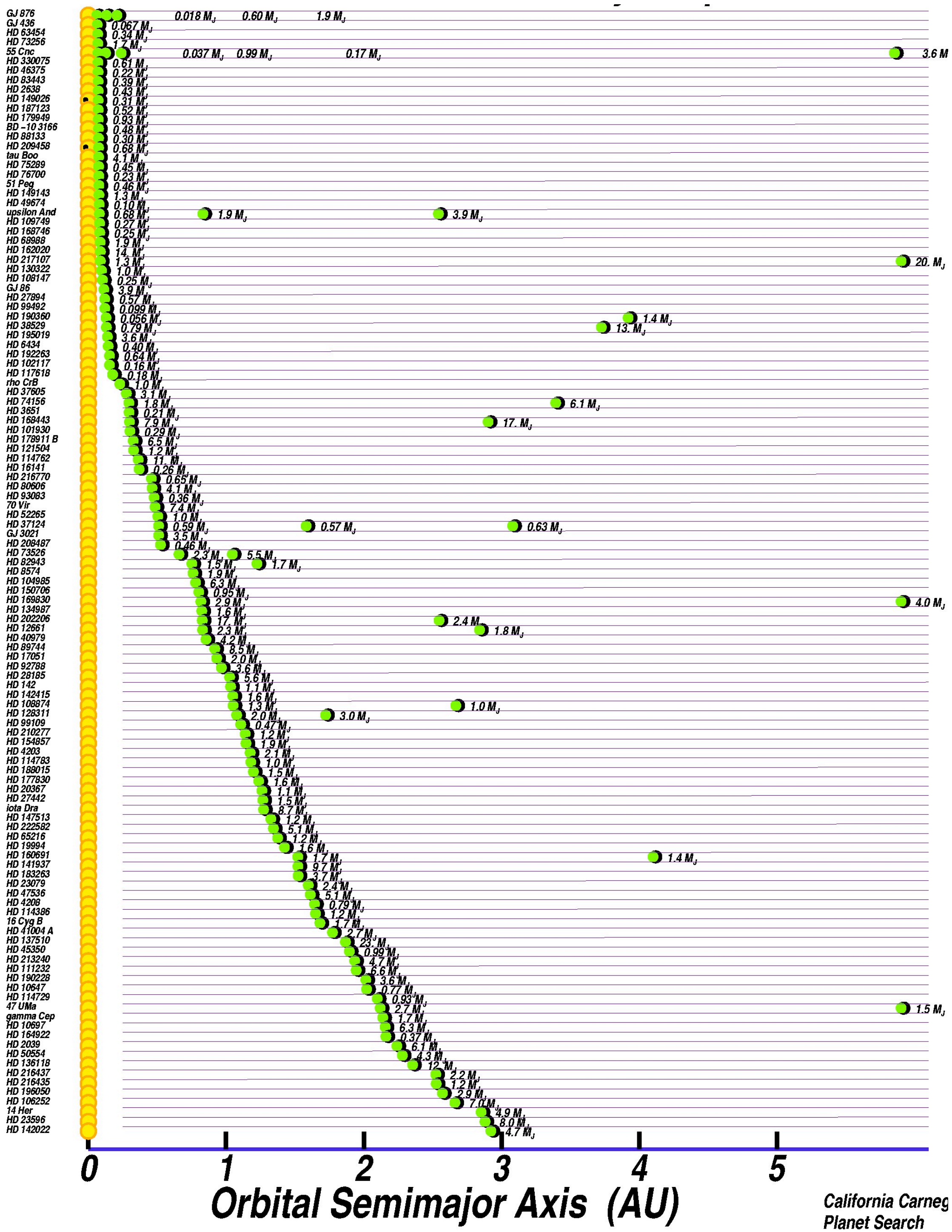
>5% of stars have detectable planets

As well as hot Jupiters, now finding more Jupiter-like planets

Also detecting sub-Neptune-mass planets

And multiple planet systems

Planets in binary systems, around giant stars, spectral types from A-M



Planet discovery space

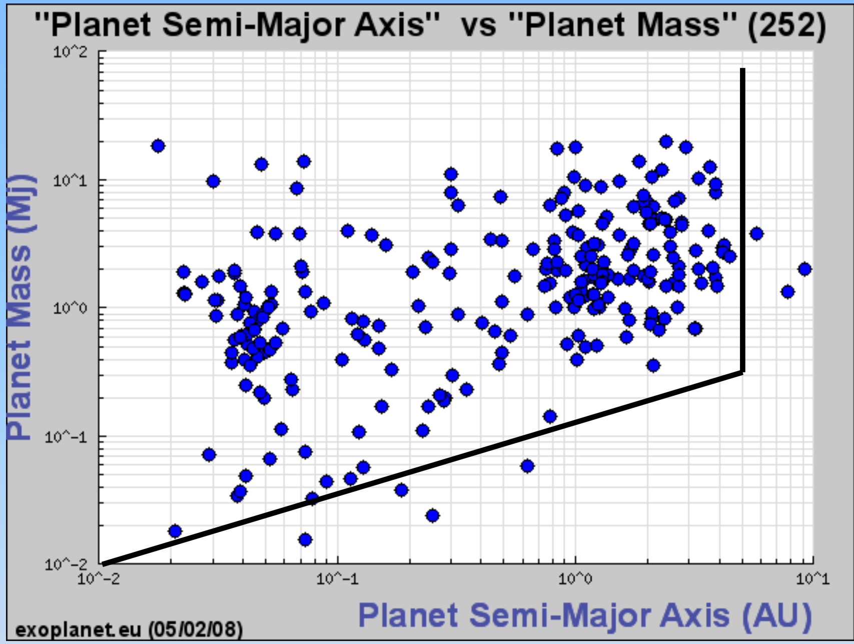
Only parts of the parameter space are sampled by this technique because of the relation:

$K = 30a_{pl}^{-0.5}(M_{pl}/M_J)(M_*/M_{sun})^{-0.5}$ m/s

and K is set by survey limits:

- lower mass limit follows $M_{pl} \propto a_{pl}^{0.5}$
- this also means lower mass planets are easier to detect around lower mass stars

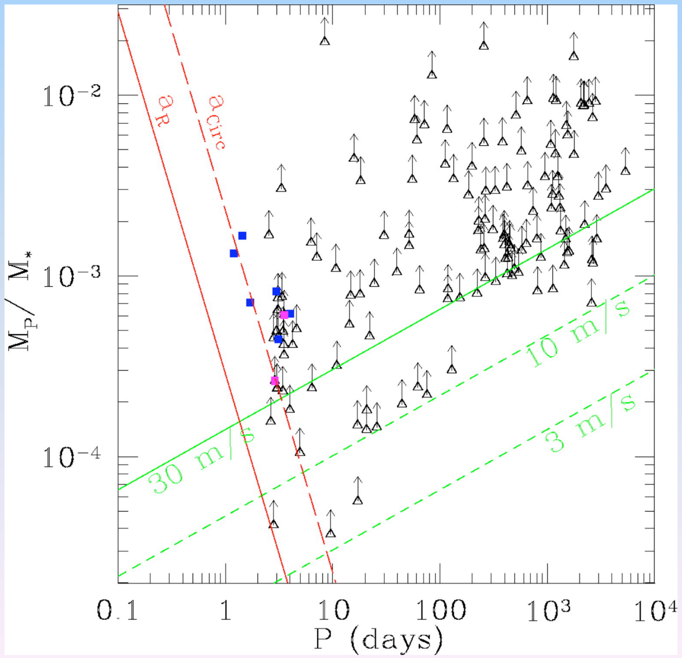
They are also limited by duration of survey, which were less sensitive in the past

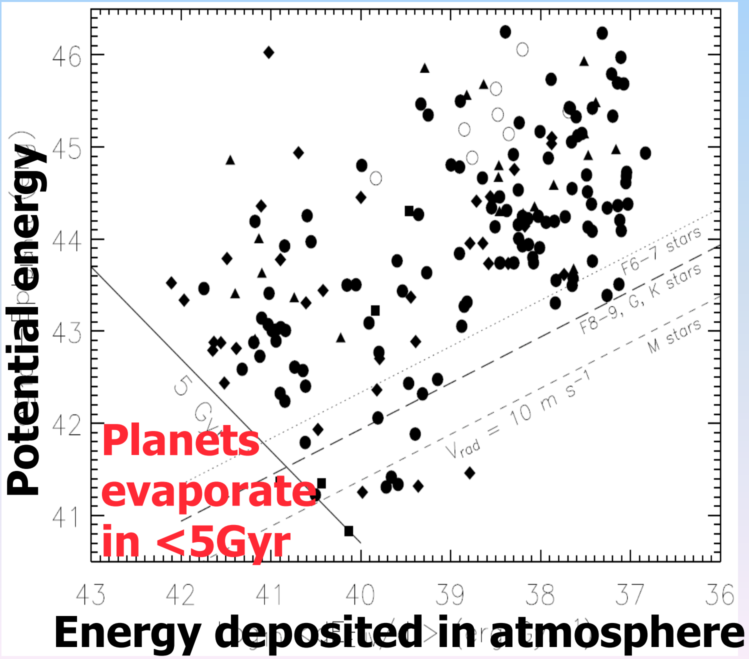


Hot Jupiter planets

~17% exoplanets are Hot Jupiters (P<10days) [1% stars]

Strong tidal interactions explains a few observations:
• Low eccentricity caused by tidal circularisation
• Lowest orbital radius at ~2xRoche limit where tidal forces would make the planet lose mass (where a_r~ $2.16R_{pl}(M_{pl}/M_*)^{-1/3}$, Faber et al. 2005, Ford & Rasio 2006; Lecavelier des Etangs 2007)

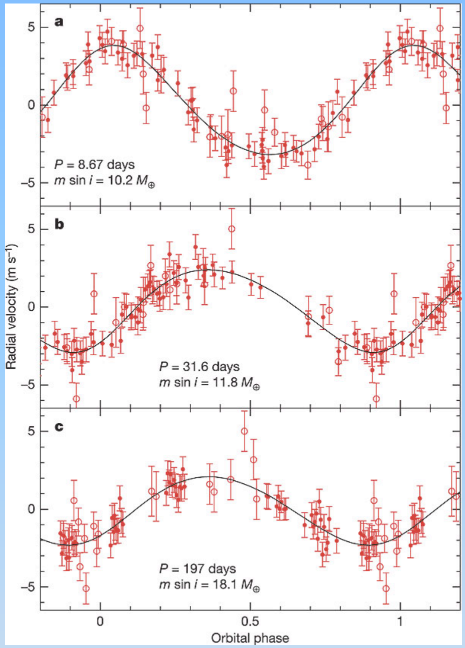




How did they form?: not enough mass in primordial disk; formed elsewhere, but followed by migration (Nelson & Papaloizou), scattering (Rasio & Ford 1996), jumping Jupiter (Marzari & Weidenschilling 2002), secular perturbations of binary (Holman et al. 1997; Nagasawa et al. 2008), capture of free-floating planet (Gaudi 2003)

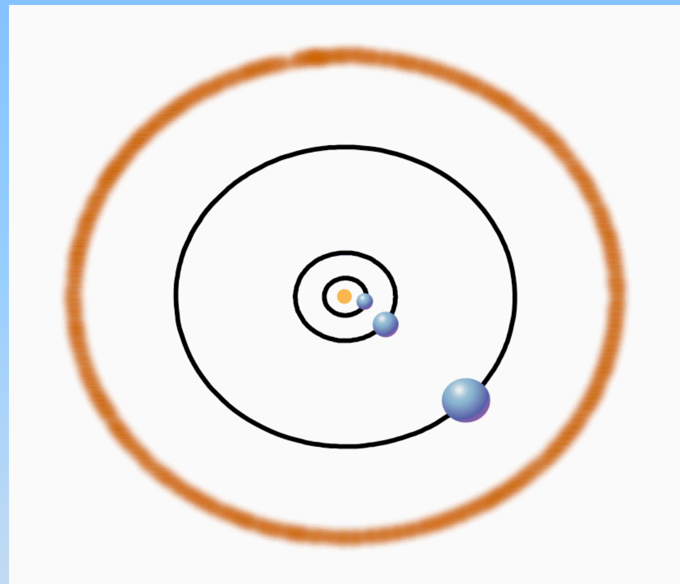
Hot Neptune planets

Current instruments (HARPS) have 1 m/s precision meaning low mass planets found [choose low activity slow rotators, split into short obs and average]

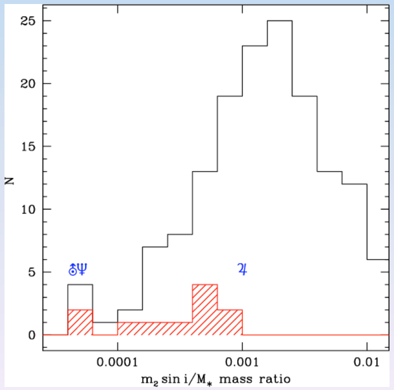


- HD69830 has 3 Neptune mass (10-18M_{earth}) planets at 0.0785, 0.186, 0.63 AU with e=0.1, 0.13, 0.07

- Growing population of hot Neptunes (McArthur et al. 2004; Santos et al. 2004; Bonfils et al. 2005; Rivera et al. 2005; Udry et al. 2006)



The lowest mass planets are found preferentially in close in orbits around low mass stars (obs bias)



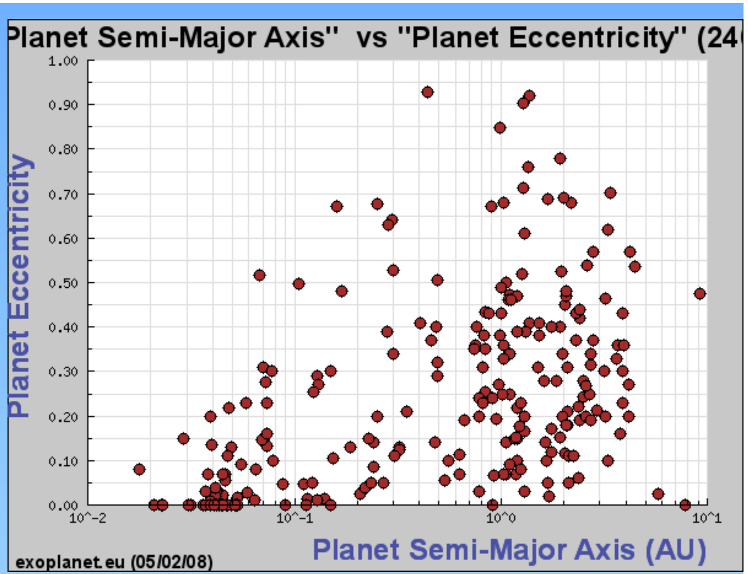
Such a population was against some planet formation models (Ida & Lin 2004) but agrees with others (Baraffe et al. 2006; Alibert et al. 2006)

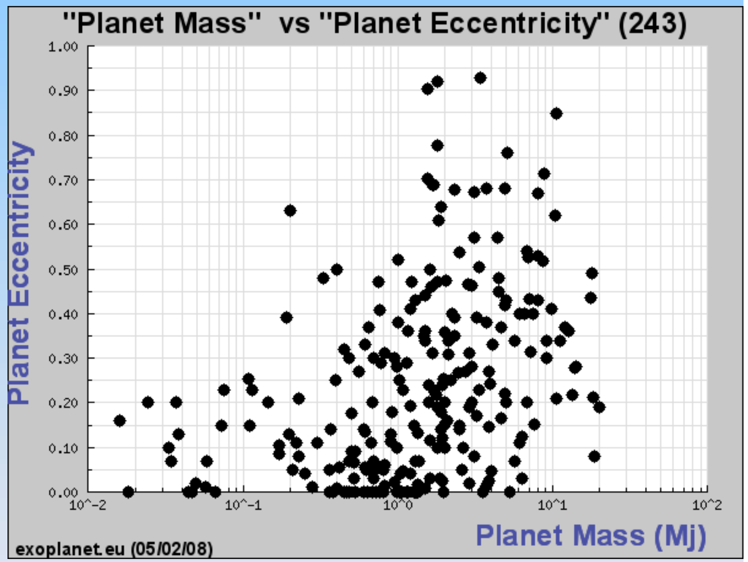
Are these super-Earths or evaporated gas giant core?

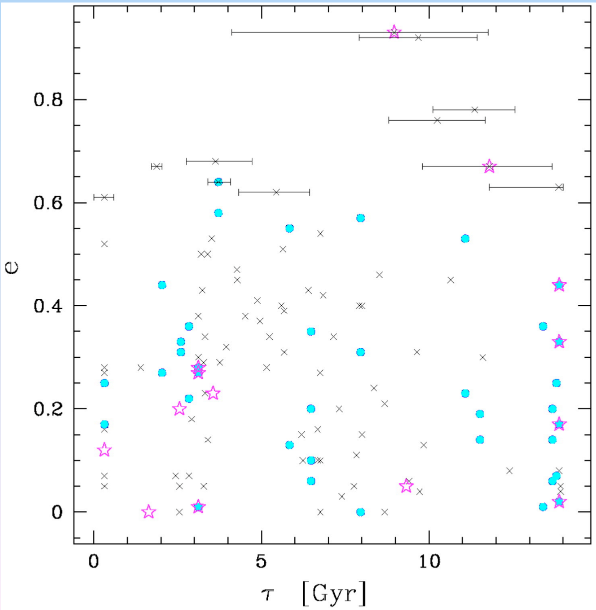
Planet eccentricity distribution

The most surprising discovery was the eccentricities: mean 0.32, up to 0.92 (Jones et al. 2006) (compared with <0.05 for giant planets in the solar system)

This is not just an observational selection effect (because the higher velocities near pericentre are easier to see and to distinguish from intrinsic variability)







No evidence for evolution in eccentricity with time (Takeda et al. 2007)

The origin of the eccentricities is not solved with theories ranging from: planet-planet interactions, planet-disk interactions, scattering by passing stars, companion stars, formation by disk instability

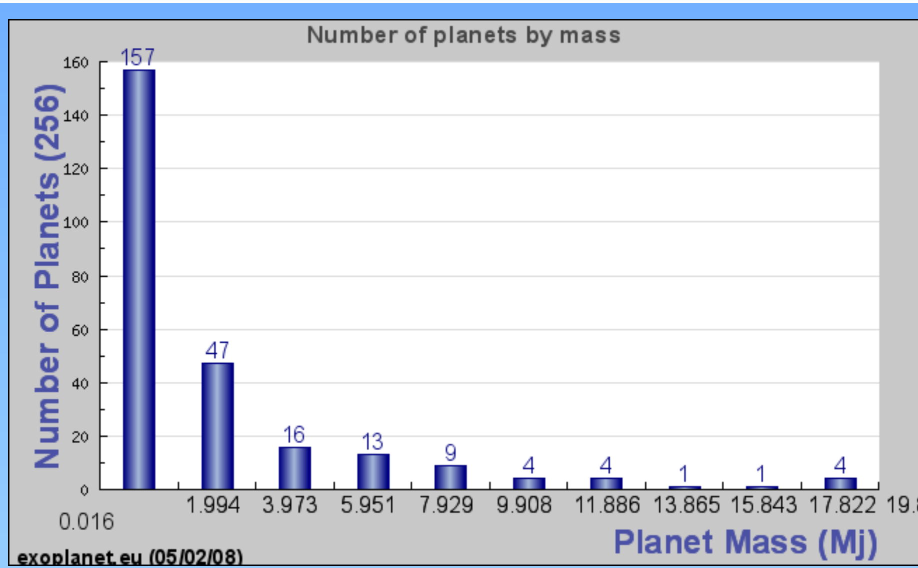
Planet mass distribution: brown dwarf desert

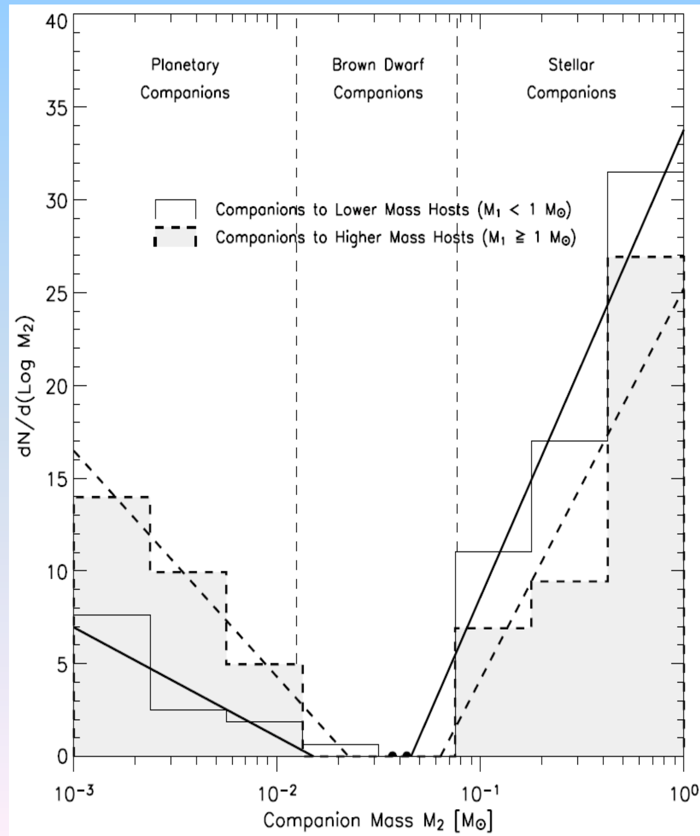
Rising function for smaller masses consistent with $dN/dM \propto M^{-1}$

Mass distribution shows lack of planets with $>8M_J$ at <3AU, commonly known as Brown dwarf dessert (Grether & Lineweaver 2006)

This desert is also being explored with imaging (e.g., McCarthy & Zuckerman 2004), showing that it is a function of distance from the star and the desert not empty large orbital radii (Metchev 2006)

It also doesn't extend to free-floating brown dwarfs which are common (Kirkpatrick et al. 1999)





Planet host metallicities

Planets most likely found around stars with high Fe/H (Gonzalez 1997), also Si/H and Ni/H (Robinson et al. 2006) and other species (Ecuvillon et al. 2004) but Li (Gonzalez 2008)?

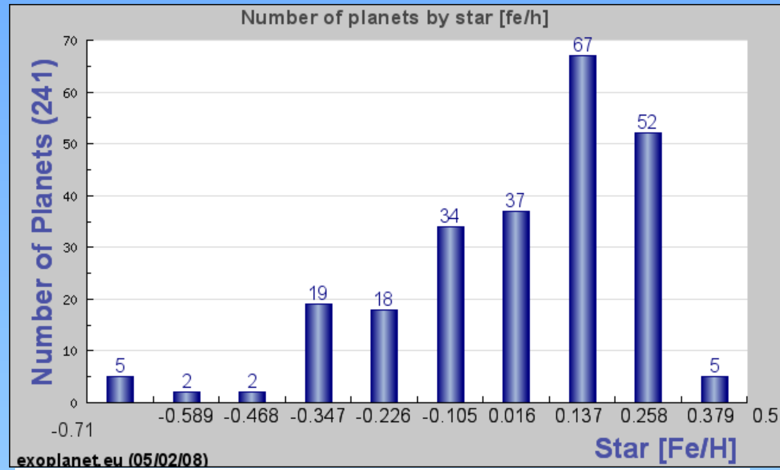
Fischer & Valenti (2005) derive:

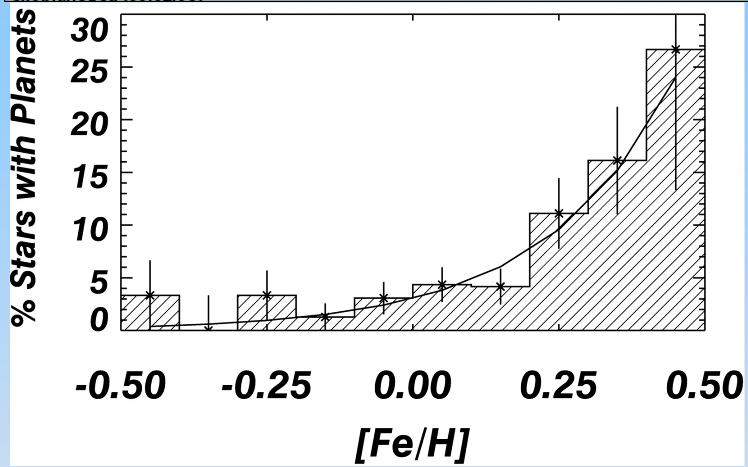
$$P_{planet} = 0.03[(N_{Fe}/N_H)_* (N_H/N_{Fe})_{sun}]^2$$

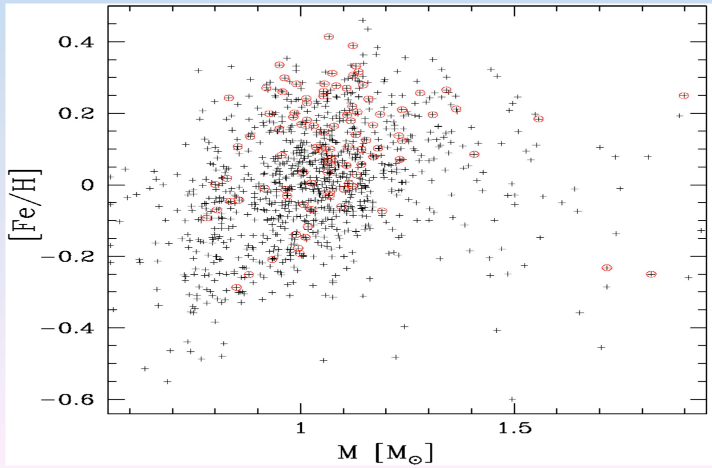
showing trend doesn't depend on depth of convection zone implying it's primordial, but Pasquini et al. (2007) found no dep for giants

Emerging trends: short period planets have higher metallicity still (Udry et al. 2006), multiple planets have higher metallicity (FV05)

Planet host stars have very similar ages to that of background F and G stars (Saffe, Gomez & Chavero 2005; Takeda et al. 2007)





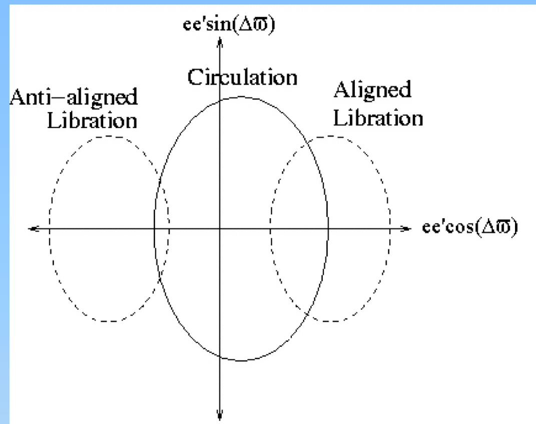


Multiple planet systems

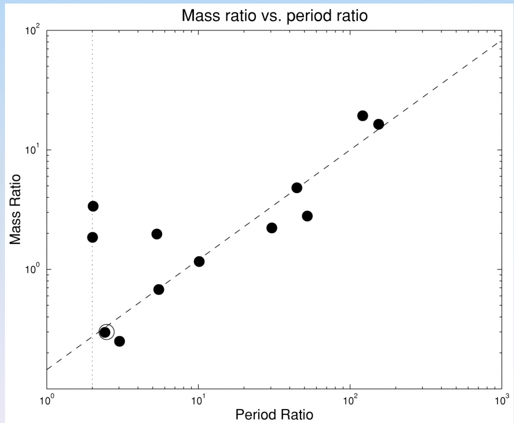
>18 extrasolar systems with multiple planetary systems

Common features are:

• Resonances (4 are in 2:1, Tinney et al. 2006; 4 in other resonances; NB 1:1 Trojans can masquerade as 2:1, Gozdziewski & Konacki 2006)
    possibly because of planet migration



• Motion near separatrix (Barnes & Greenberg 2006)
    4/18 systems like this
    possibly because of sudden eccentricity increase



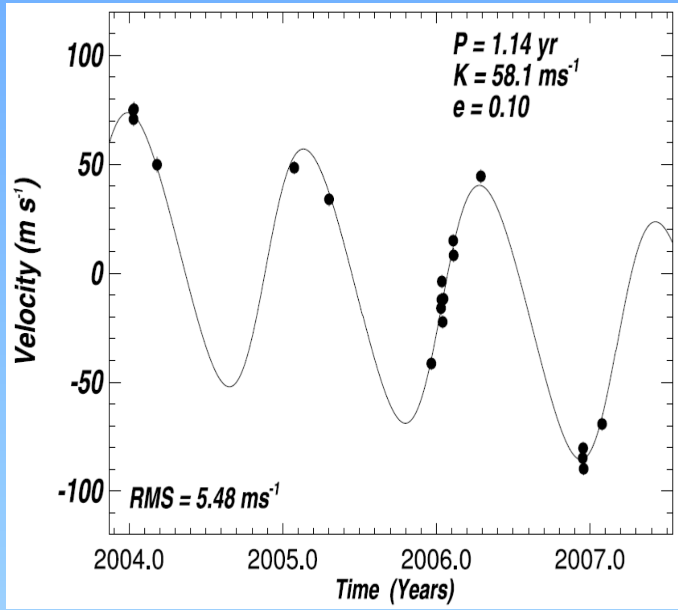
• Correlation in mass ratio/period ratio (Mazeh & Zucker 2003)?

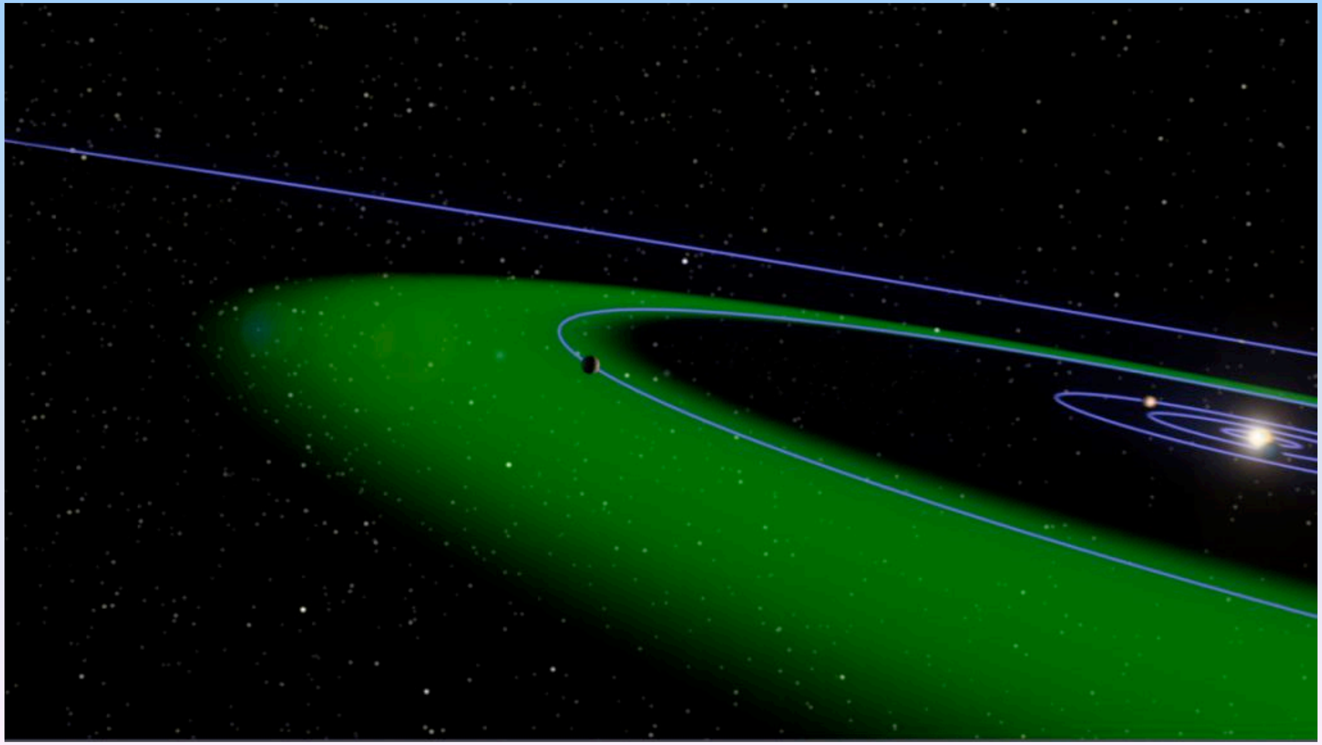
• Correlation with other parameters such as [Fe/H] and M_{pl} and e

Multiple planet systems

8 stars with 3 or more planets (Bean et al. 2008), and many stars show residuals indicative of long period planets (e.g., Robinson et al. 2007)

28 multiple planet systems (Wright et al. 2009)

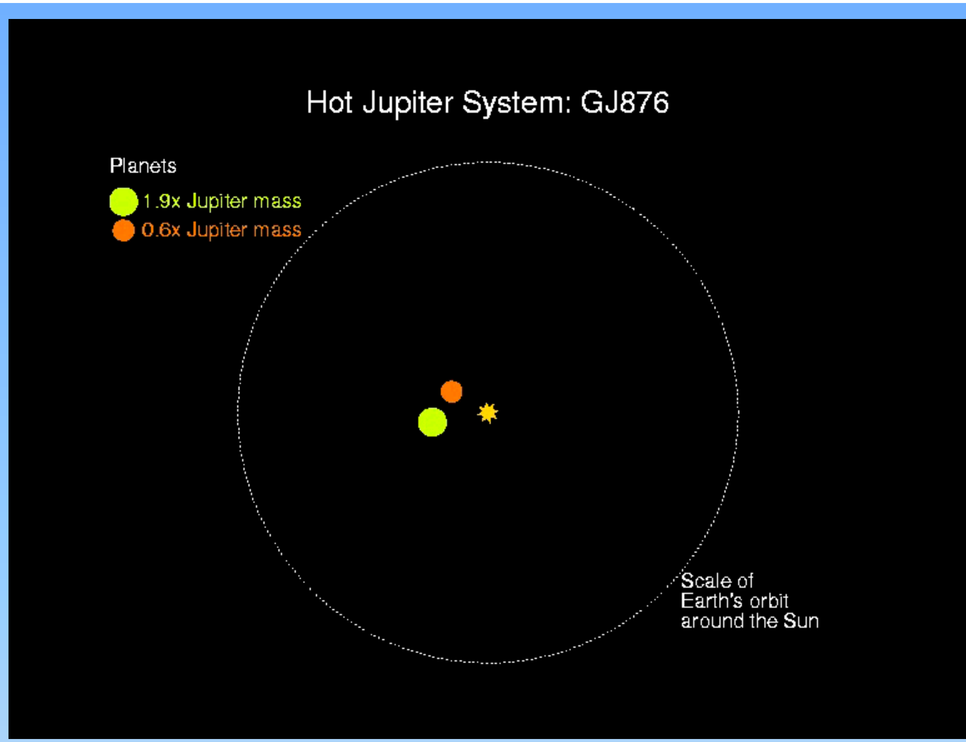




55 Cancri has 5 planets (Fischer et al. 2007), one of which may be in the habitable zone

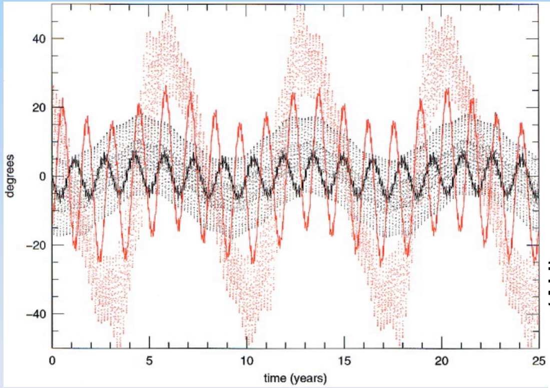
a_{pl} (AU)	M_{pl} (M_J)	e_{pl}
0.038	0.034	0.07
0.115	0.824	0.014
0.240	0.169	0.086
0.781	0.144	0.2
5.77	3.835	0.025

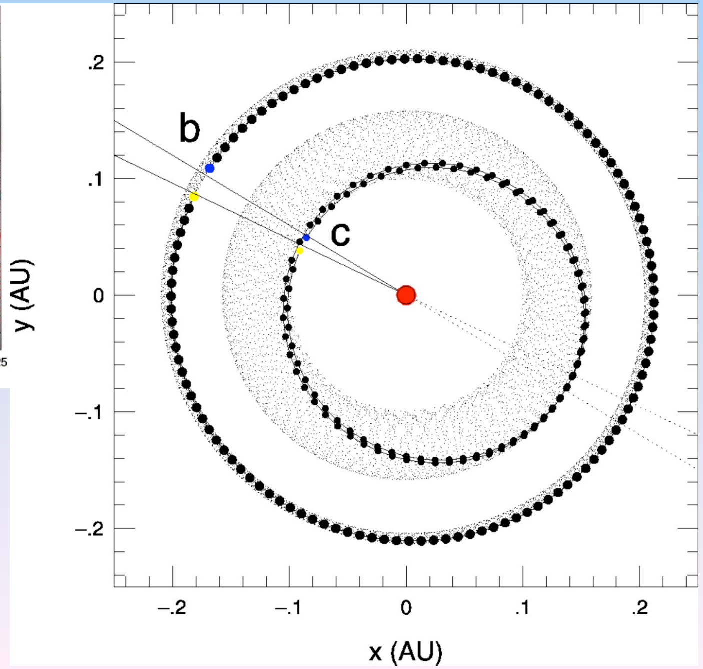
Resonant planets



8/18 of the multiple planets are found in resonance, e.g., the two Jupiter planets around GJ876 are in 2:1 resonance and as for the resonant pulsar planets detection of their mutual gravitational interaction allowed the masses and orbital inclinations of the planet to be derived

The planets are in both 2:1 mean motion eccentricity resonance and secular resonance (Laughlin & Chambers 2001)





The pericentres oscillate about alignment $\varpi_b-\varpi_c=0^0$ with maximum amplitude $|\varpi_b-\varpi_c|_{max}=34^0$ and the line of apsides precesses at a rate $d\varpi/dt=-41^0/yr$ (Laughlin et al. 2005; Beauge et al. 2006)

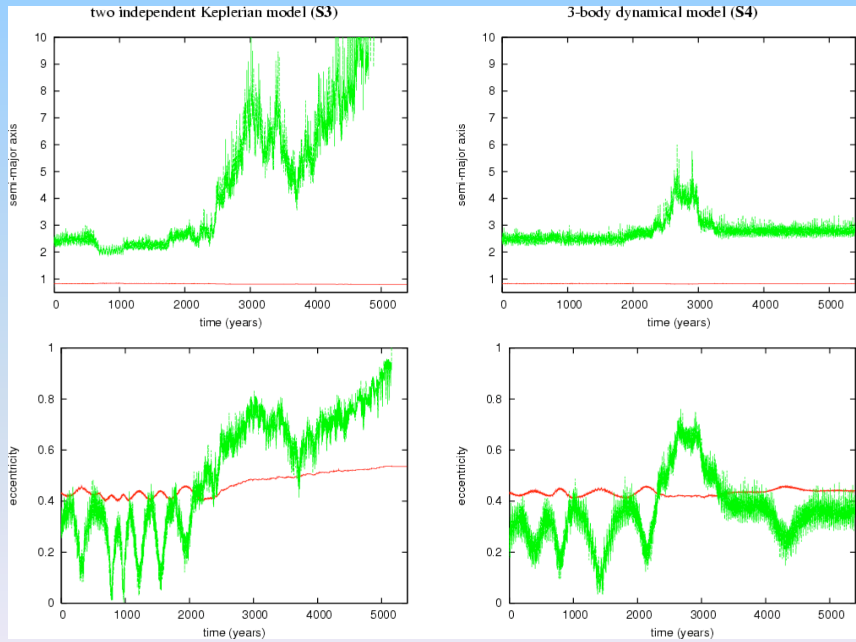
Circumbinary/resonant planet

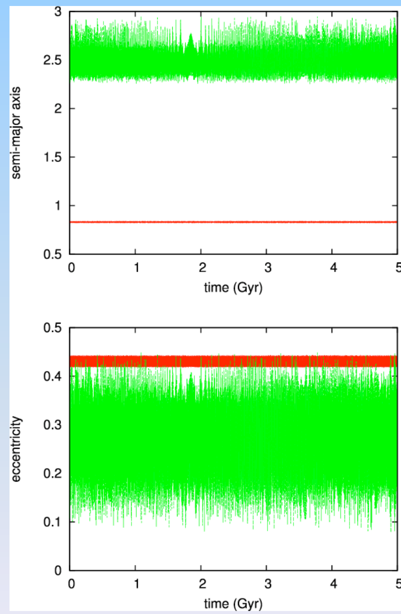
A multiple planet system around HD202206 may better be described as a circumbinary planet… and this is in 5:1 resonance (Correia et al. 2005):

Star: G6V, 1.15M_{sun}, 5.6Gyr
Planet 1: 17.4M_J, 0.83AU, e=0.43
Planet 2: 2.44M_J, 2.55AU, e=0.27

Is planet 1 a superplanet or did planet 2 form in a circumbinary disk?

Either way, the system must be in 5:1 resonance because orbital solutions that are not in resonance become unstable on timescales of 40,000yrs

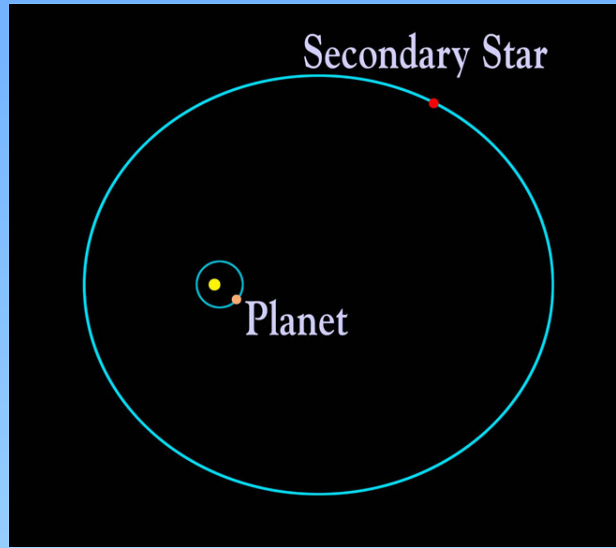




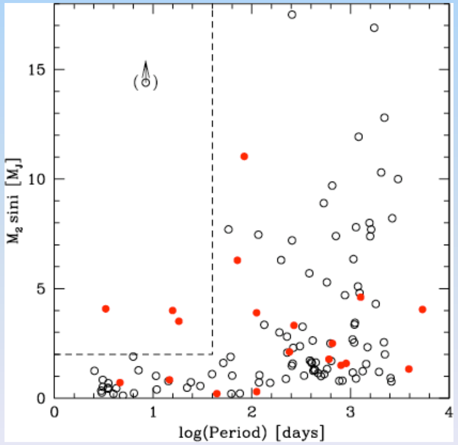
Similarly HD108874 is strongly affected by 4:1 resonance, while υ And, HD12261 and HD169830 may be close to 5:1 and 9:1 resonances (Libert & Henrard 2007)

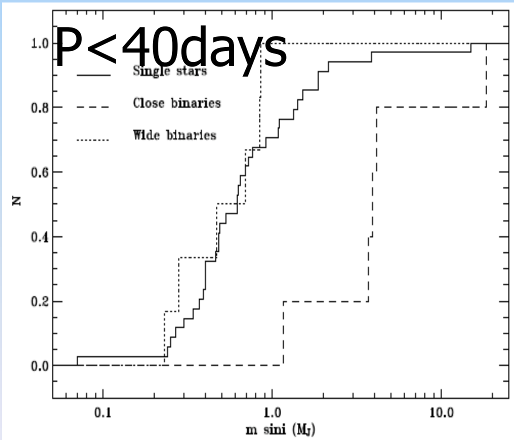
Planets around binary stars

Planetary systems are also being detected in wide binary systems with ~19/115 planets in multiple stellar systems, and single stars now discovered to be binaries (eg., Mugrauer et al. 2005; Chauvin et al. 2006); e.g. γ Cephei ($1.7M_J$ at 2.1AU, companion at 28AU, one of closest binaries to have orbiting planet Hatzes et al. 2003)



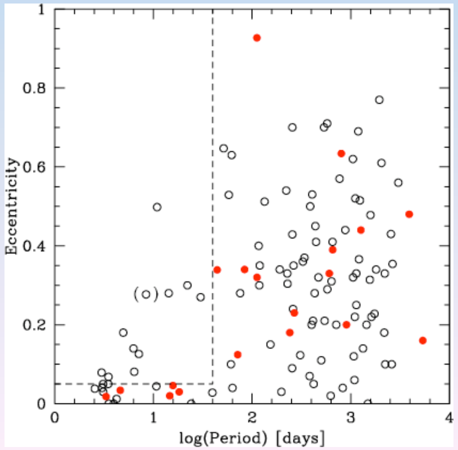
Emerging trends (Eggenberger et al. 2004; Desidera & Barbieri 2007):

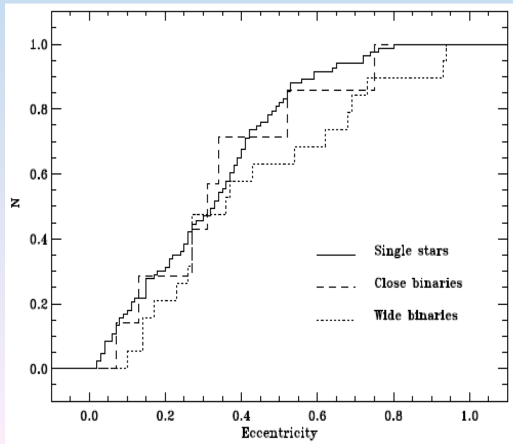




few high mass close in planets, with those that are being in (close) binary systems

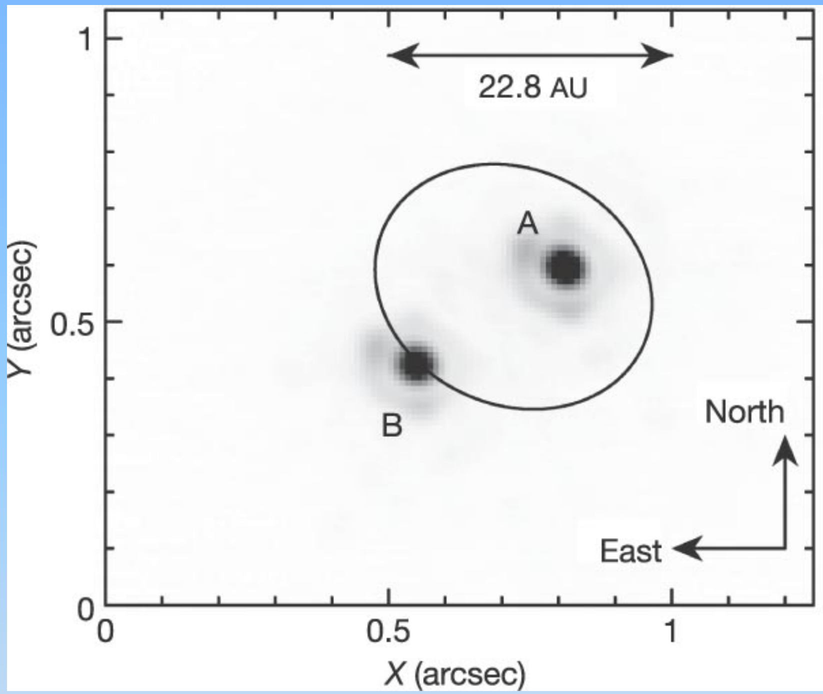
close in planets in binary systems are low eccentricity, but wide binary planets have high eccentricity





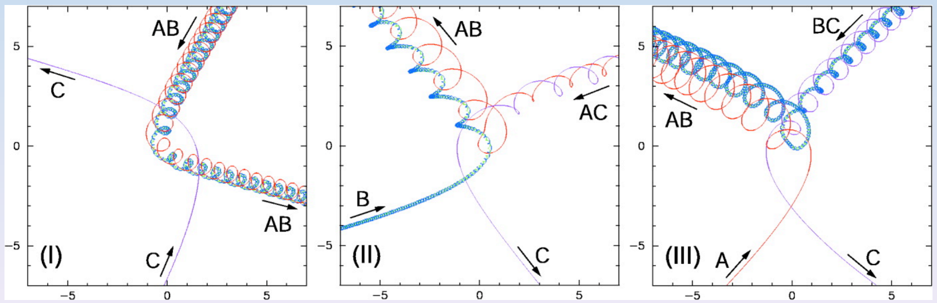
Planet in a triple system

A planet has also been found in hierarchical triple system HD188753



Konacki (2005) showed that a $1.14M_J$ planet orbits the primary ($1.06M_{sun}$) at 0.045AU (i.e., Hot Jupiter), but that there is also a wide binary B which is itself a binary system (0.96 and $0.67M_{sun}$ at 0.67AU) with orbit a=12.3AU, e=0.5 (but see Eggenberger et al. 2007)

Problem is that binary would have truncated the proto-planetary disk at 1.3AU, so how did planet get there?



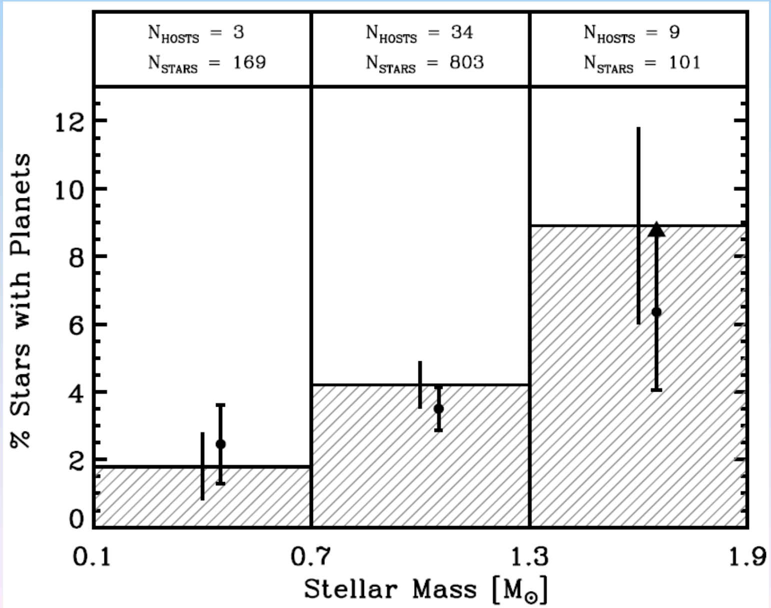
Pfahl (2005) suggest origin is in an exchange reaction: star was originally single and exchanged places with outlying member of another hierarchical triple

Planets around M stars

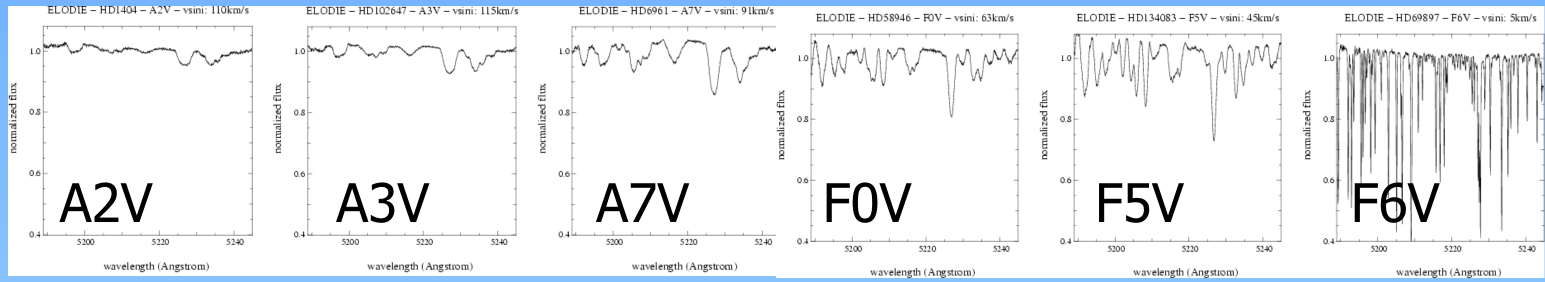
6/300 M stars with planets (Marcy et al. 1998, Rivera et al. 2005; Butler et al. 2004; Bonfils et al. 2005; Butler et al. 2006; Bonfils et al. 2007; Udry et al. 2007; Johnson et al. 2007)

	[Fe/H]	M_{pl}	a, AU	e
GJ876b	-0.12	$1.94M_{jup}$	0.208	0.025
GJ876c		$0.62M_{jup}$	0.130	0.224
GJ876d		$0.44M_{nep}$	0.021	0
GJ436	-0.32	$1.2M_{nep}$	0.028	0.12
GJ317	-0.23	$1.2M_{jup}$	0.95	0.193
Gl581	-0.33	$0.99M_{nep}$	0.041	0
GJ674		$0.61M_{nep}$		
GJ849	0.16	$0.82M_{jup}$	2.35	0.06

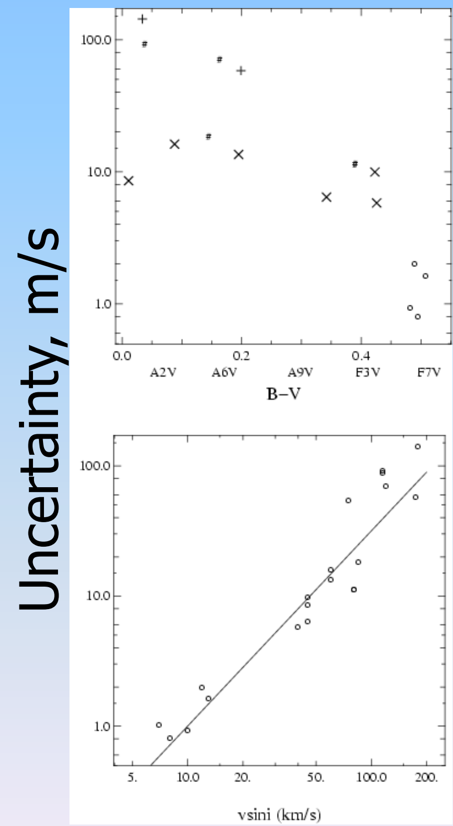
- 3 times less common than around FGKs (Endl et al. 2006) or 5 times less common than around AFs (Johnson et al. 2007)
- Lower [Fe/H] than planets around FGK stars (Bean et al. 2007)
- Hot Neptunes rather than Hot Jupiters
- Deficit of long period planets?



Planets around F and A stars



Planet searches are limited to spectral types >F7 because earlier types have fewer lines and faster rotation meaning large intrinsic uncertainty in radial velocity measurements



Galland et al. (2005) present results of survey of A-F stars with detection of around 3Gyr F6V ($1.25M_{sun}$) HD33564 of $9.1M_J$ at 1.1AU with e=0.34; [Fe/H]=-0.12

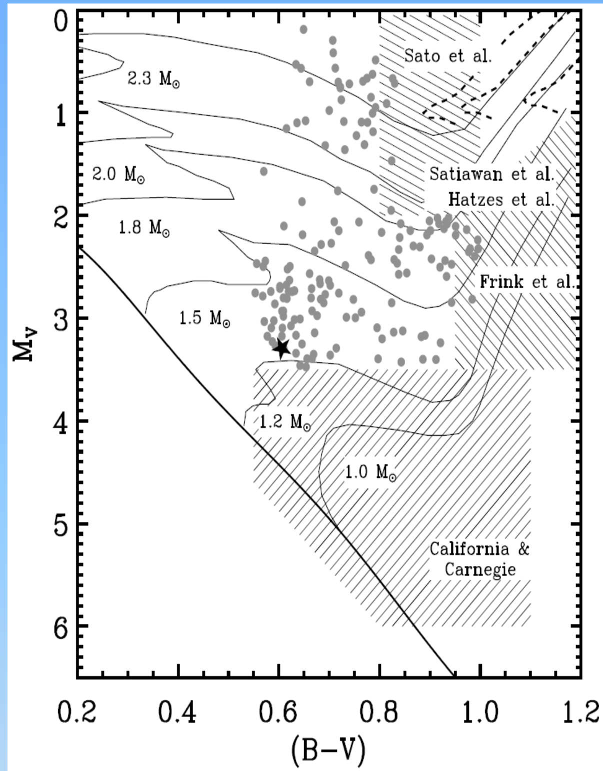
Galland et al. (2006a) searched β Pic (A5V with disk and evidence for planets) and set constraints $<2M_J$ at 0.05AU and $<9M_J$ at 1AU but found high frequency δ Scuti pulsations and large intrinsic variability

Galland et al. (2006b) report detection of $25M_J$ at 0.22AU from A9V HD180777

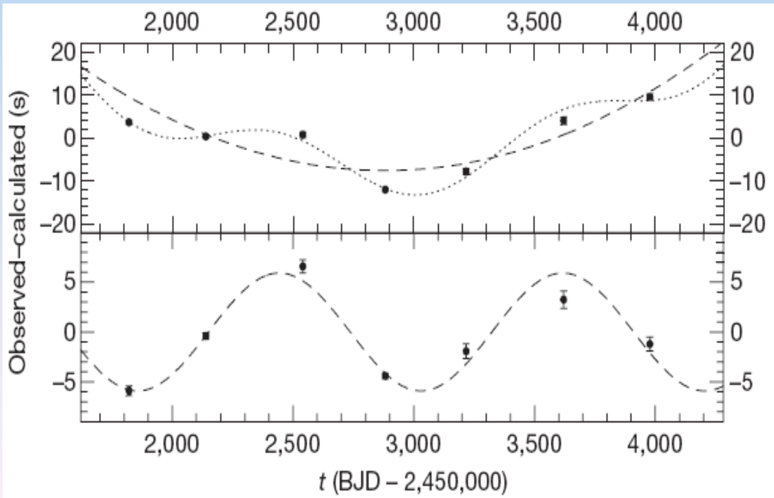
Planets of post-MS stars

Planets are also found around giant and subgiant stars, eg:

- K2III Iota Dra ($1.05M_{sun}$, $70L_{sun}$) has $8.9M_J$ ($<45M_J$) at 1.3 AU with e=0.7 (Frink et al. 2002)
- G2III HD104985 ($1.5\text{-}3M_{sun}$) has $6.3\text{-}9.6M_J$ at 0.78 AU with e=0.03 (Sato et al. 2003)
- K2II HD13189 ($2\text{-}7M_{sun}$) has $7\text{-}20M_J$ at 1.5-2.2 AU (Hatzes et al. 2005)
- G0IV HD185269 ($1.28M_{sun}$) has $0.94M_J$ at 0.077 AU with e=0.3 (Johnson et al. 2006)



Interesting because of orbital evolution, response to high luminosity, probes of higher mass stars (when T_{eff} has gone down so that more lines, Hatzes et al. 2006), possibility of detecting transits (due to large radius)



Plus extreme horizontal branch star V391 (Silvotti et al. 2007) has $3.2M_{Jup}$ planet at 1.7AU

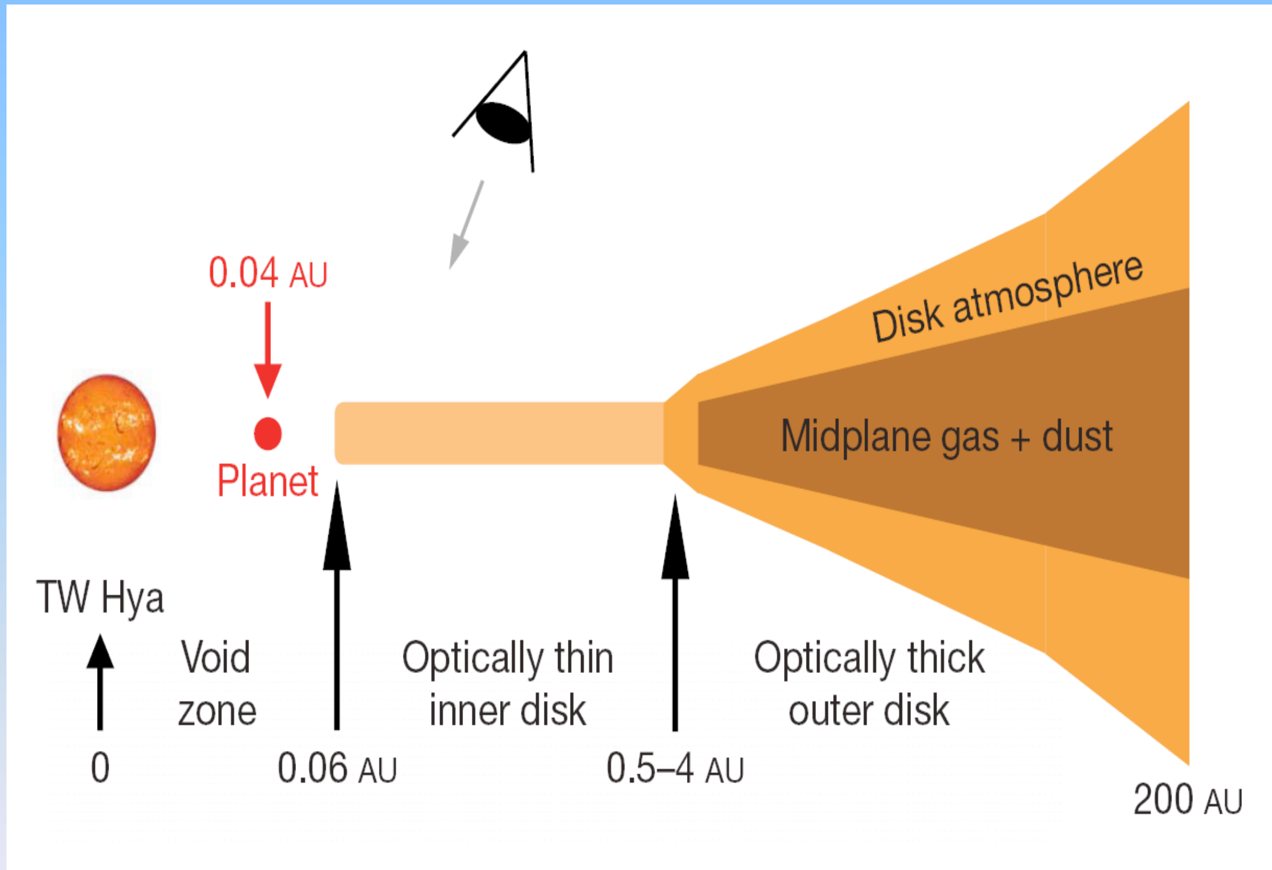
Planets of pre-MS stars

A planet has also been reported in a pre-main sequence star, TW Hydrae, which also has a protoplanetary disk (Setiawan et al. 2008)

This planet would tell us about the timescale for formation of Hot Jupiters, and about planet disk interactions, and disk clearing mechanism, but there are doubts

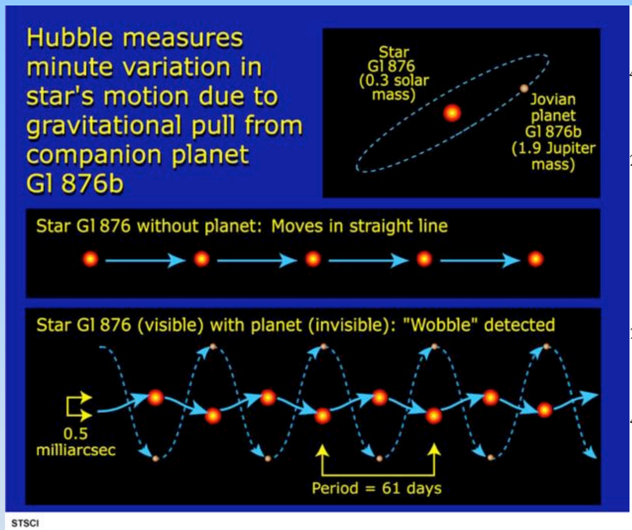
Other pre-main sequence planets also searched (e.g., Prato et al.)

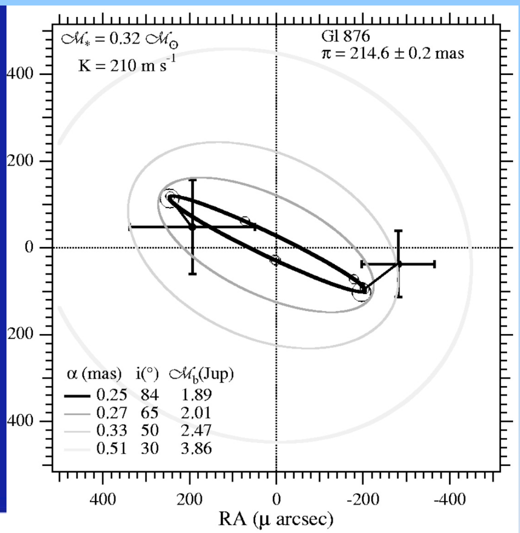
$9.8M_{Jup}$ at 0.04AU at 8-10Myr?



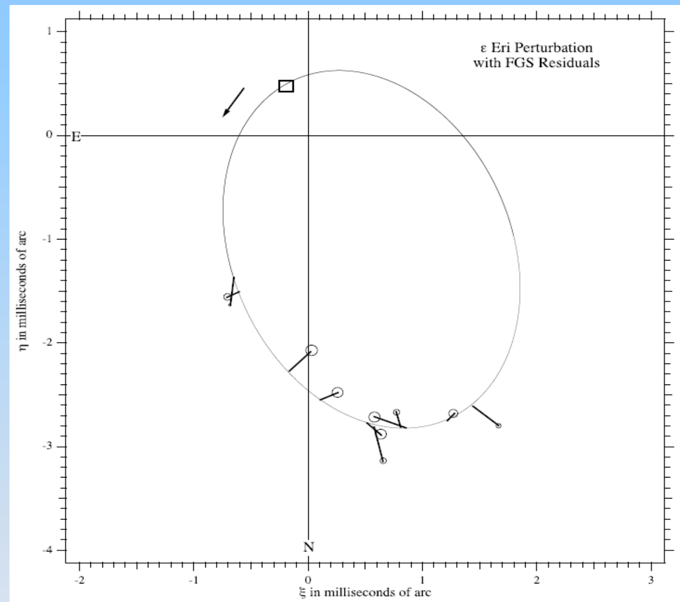
Astrometric detection of known planets

Hipparcos constraints on doppler planets showing low I implying stellar mass "planets" (Mazeh et al. 1999; Gatewood et al. 2001; Han et al. 2001) later ruled out (Pourbaix 2001)





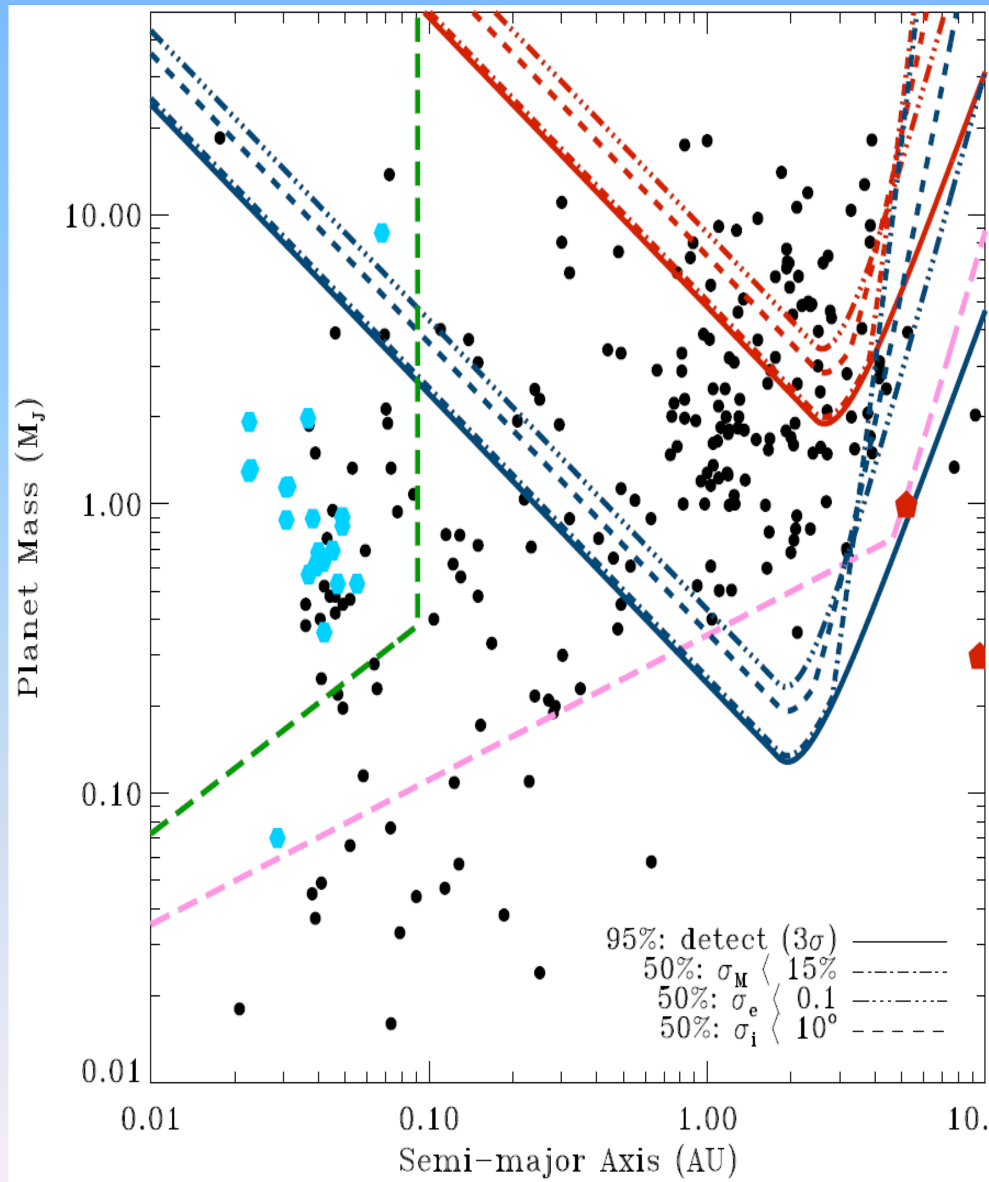
Astrometric detection of known planet of GJ876 using HST FGS (Benedict et al. 2002) finds perturbation of 250±60μas, i=86^0, 1.89M$_J$



Monitoring known planets with FGS also confirmed eps Eri planet (Benedict et al. 2007)

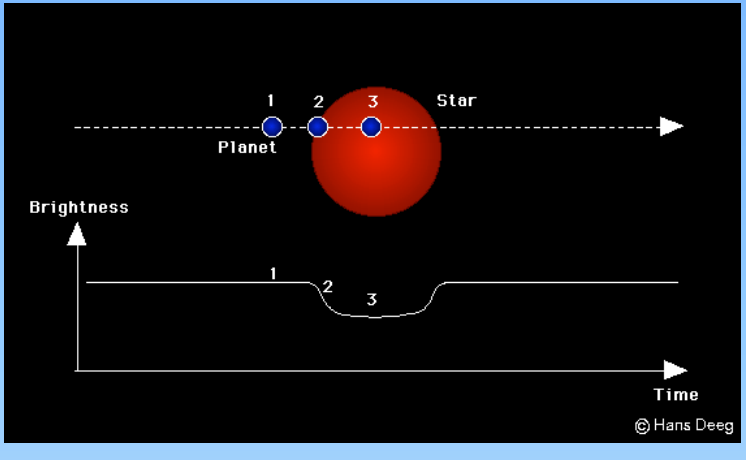
Future of astrometric detection

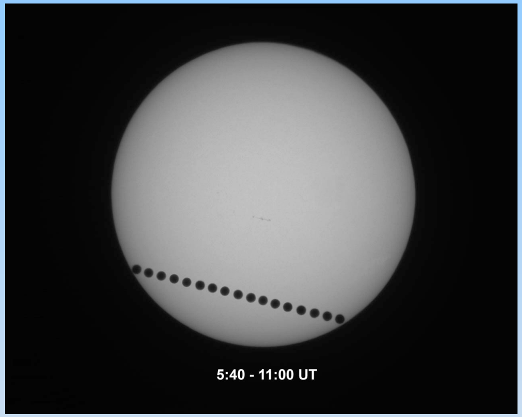
- FGS (ongoing)
- VLTI (has programmes ongoing)
- ALMA (possible)
- VLBA (10μas)
- GAIA (8μas, Casertano et al. 2008)
- SKA (1μas) (Bower et al. 2007)
- SIM (1-3μas, Unwin et al. 2007)



Transit detection method

Planets can also be detected by the dimming of the starlight when the planet passes in front of the star, such as this transit of Venus in June 2004:





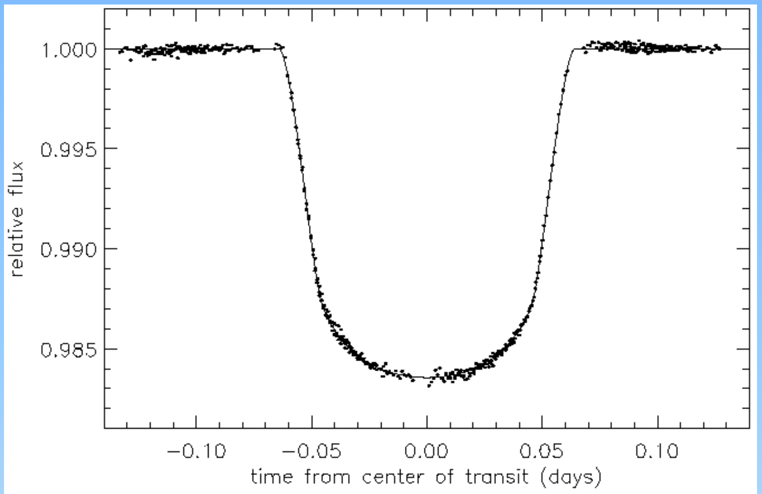
To see a transit in an extrasolar system, the orientation of the planet's orbit has to be just right; Hot Jupiters are around 1% of stars, and their proximity to parent star means 10% should transit meaning 1 in 1000 stars should exhibit transits

How do we know it's a planet? other possibilities: grazing eclipsing binary, eclipsing binary in multiple systems, low mass binary (Pont et al. 2006)

depth, duration, shape, colour, multiple events

Planetary Transits

HD209458b is a hot Jupiter planet that was first detected by doppler wobble technique, but the transit of this planet in front of the star (lasting 3 hours every 3.5 days) has since been observed (Charbonneau et al. 2000)



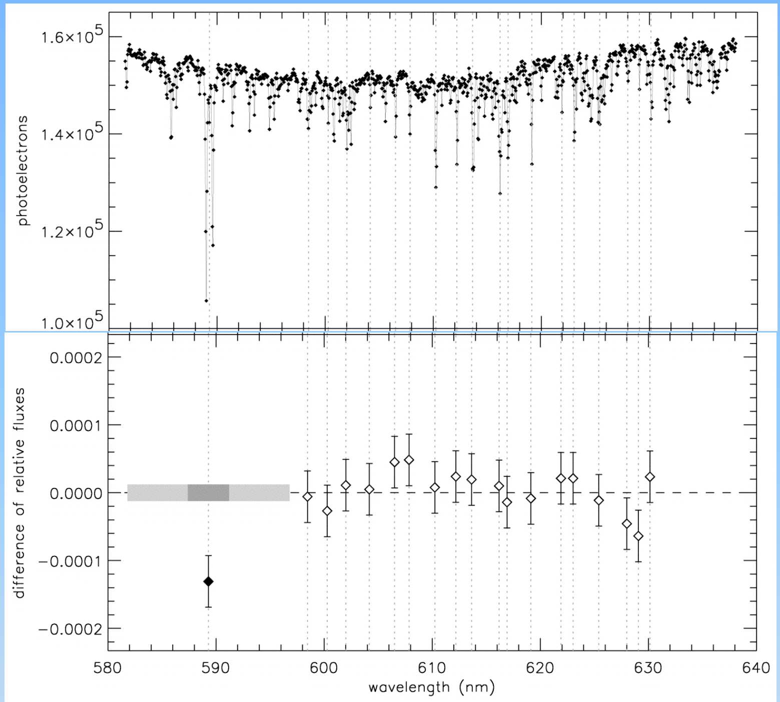
This confirms the planetary nature of the doppler observations and gives unambiguous measure of mass and size of planet (and so density)

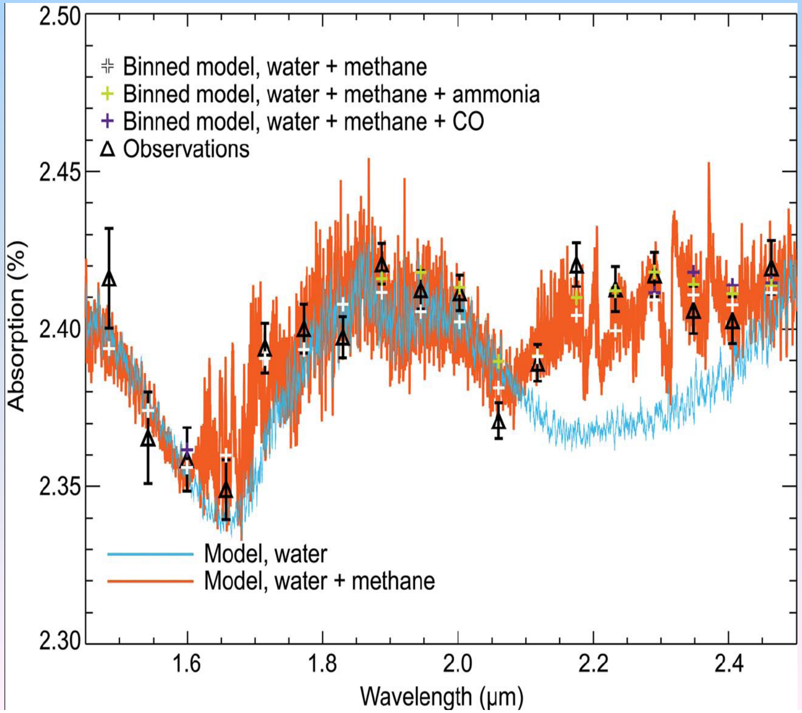
Also allows other studies:

- Search for satellites, rings, Trojans (Brown et al. 2001; Ford & Holman 2007)
- Period variations due to additional planets (Wittenmyer et al. 2001)
- Atmospheric absorption features (Deming et al. 2005)
- Exosphere detection (Vidal-Madjar et al. 2003)
- Angle between orbital plane and stellar rotation (Winn et al. 2005)
- Spectroscopic signatures near secondary transit (Richardson et al. 2003)
- Detection of thermal emission from planet (Charbonneau et al. 2005)

Atmospheric composition of HD209458

Charbonneau et al. (2002) used HST spectra of NaD line both in and out of transit to detect the additional absorption of 0.02% during transit due to sodium in the atmosphere of the planet; models of planetary atmospheres (and stellar limb darkening) produce significantly deeper absorption

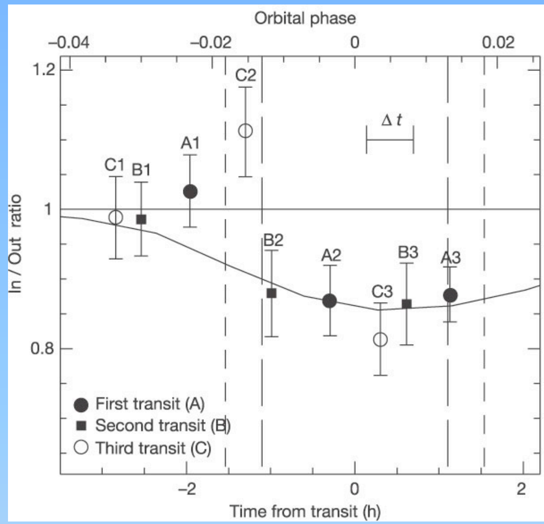


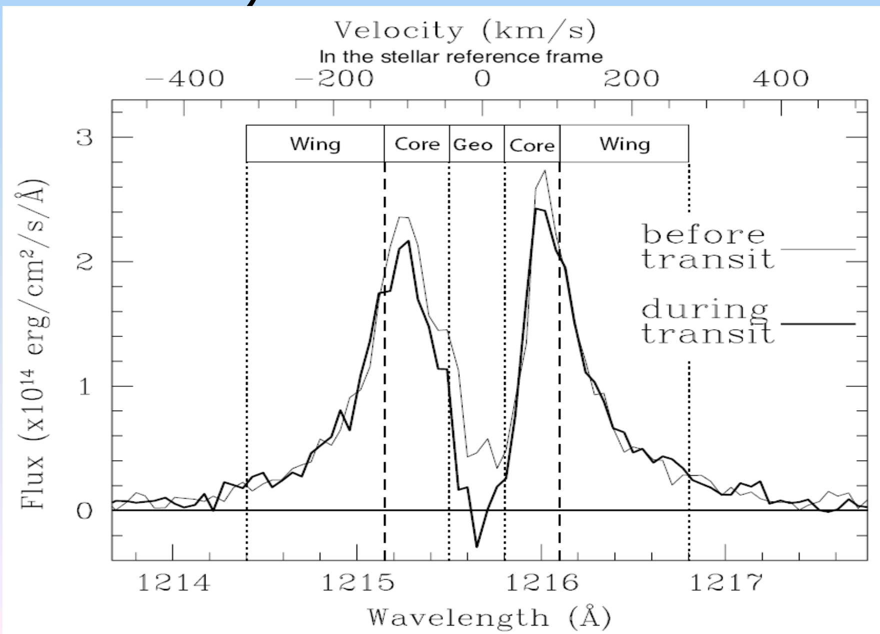


Detection of H_2O in atmos of HD189733 (Tinetti et al. 2007) as well as methane from NICMOS spectrum (Swain et al. 2008), but flat transmission spectrum 0.55-1.05μm indicative of haze hiding features (Pont et al. 2008)

Exosphere of HD209458

Vidal-Madjar et al. (2003) detected atomic hydrogen in absorption (15%) in stellar Lyman α line -> beyond Roche limit so from escaping hydrogen atoms; also escaping oxygen and carbon (Vidal-Madjar et al. 2004), an effect compounded by Roche lobe (Erkaev et al. 2007)

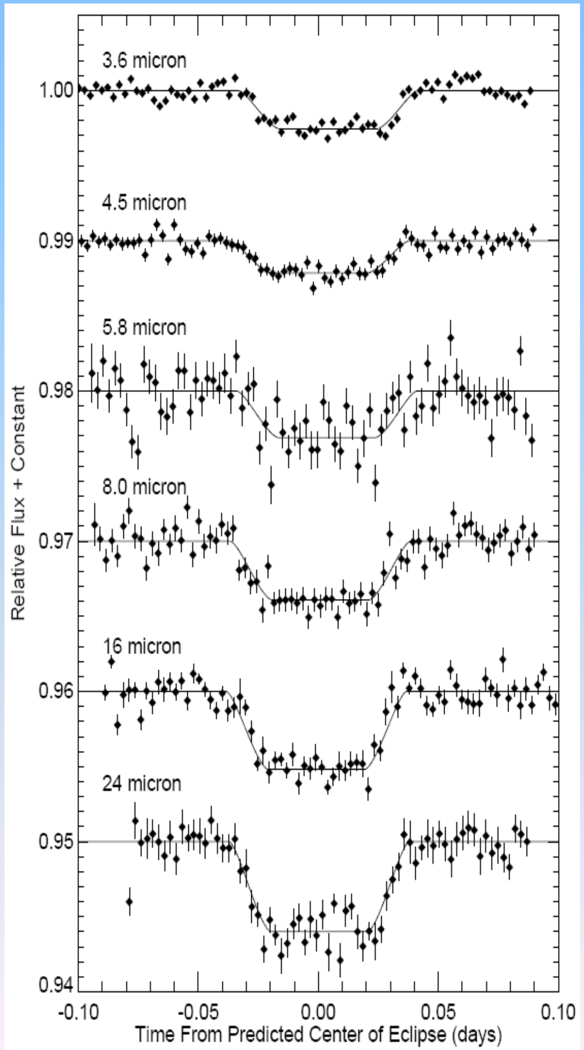




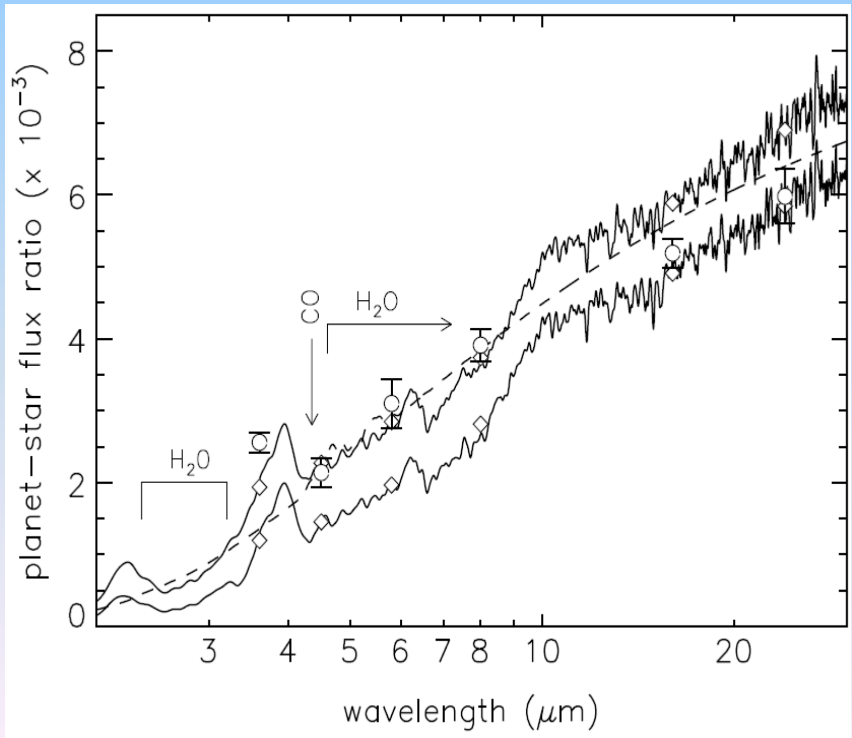
This result was challenged by Ben-Jaffel et al. (2007) who measured 8% absorption from the same data, but upheld by Vidal-Madjar et al. (2008) who claimed the difference is due to velocities used in this measurement

Secondary planetary transits

Secondary transit = detection of dimming of IR flux when the planet passed behind the star (Deming et al. 2005; Charbonneau et al. 2005)

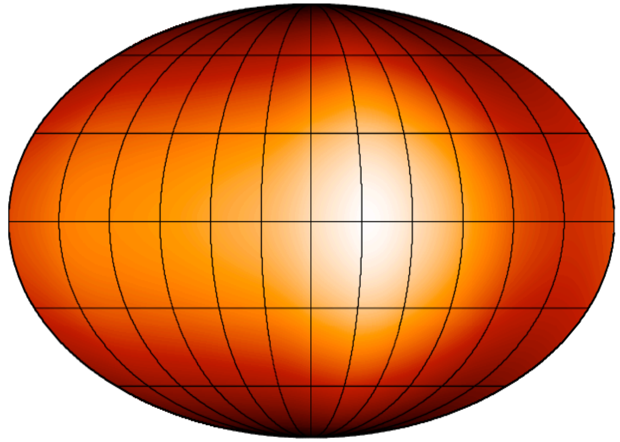


Spitzer is used to get depths at 3.6-24μm building up a spectrum of emission from planet (e.g., Charbonneau et al. 2008)

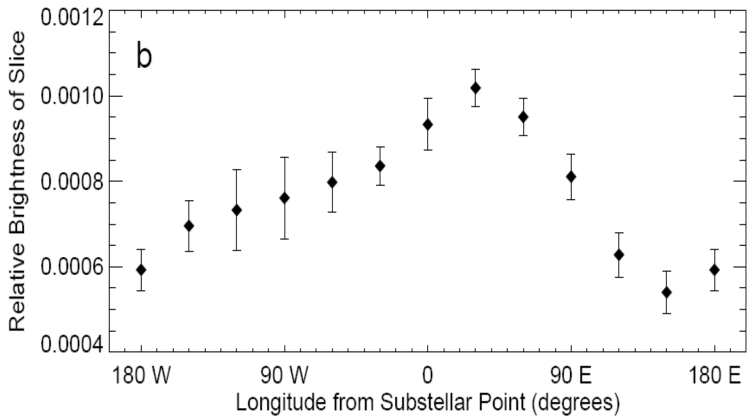


This gives temperature which can be used to assess heating by stellar irradiation, as well as chemical composition

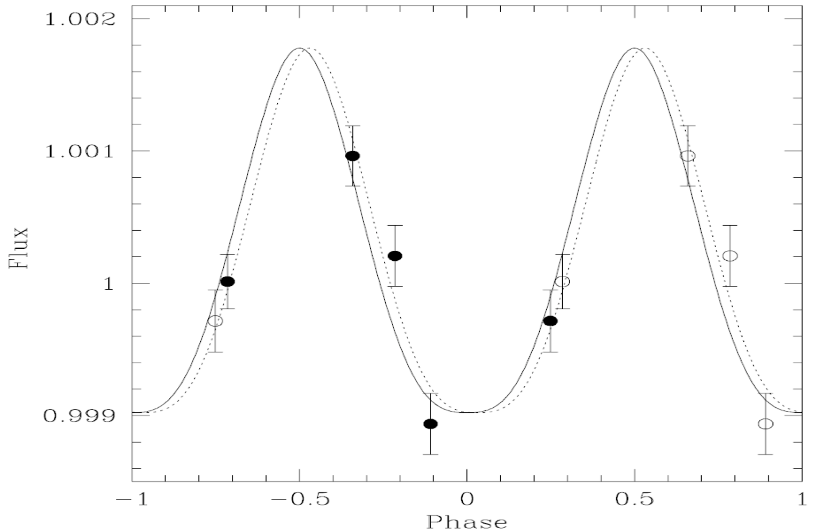
Mapping planetary surface



Planets should show strong day/night variation, which is important for understanding energy transport processes, particularly pertinent for tidally locked planets



Temporal variations in infrared flux throughout orbit are indicative of night/day side temperatures (Harrington et al. 2006)

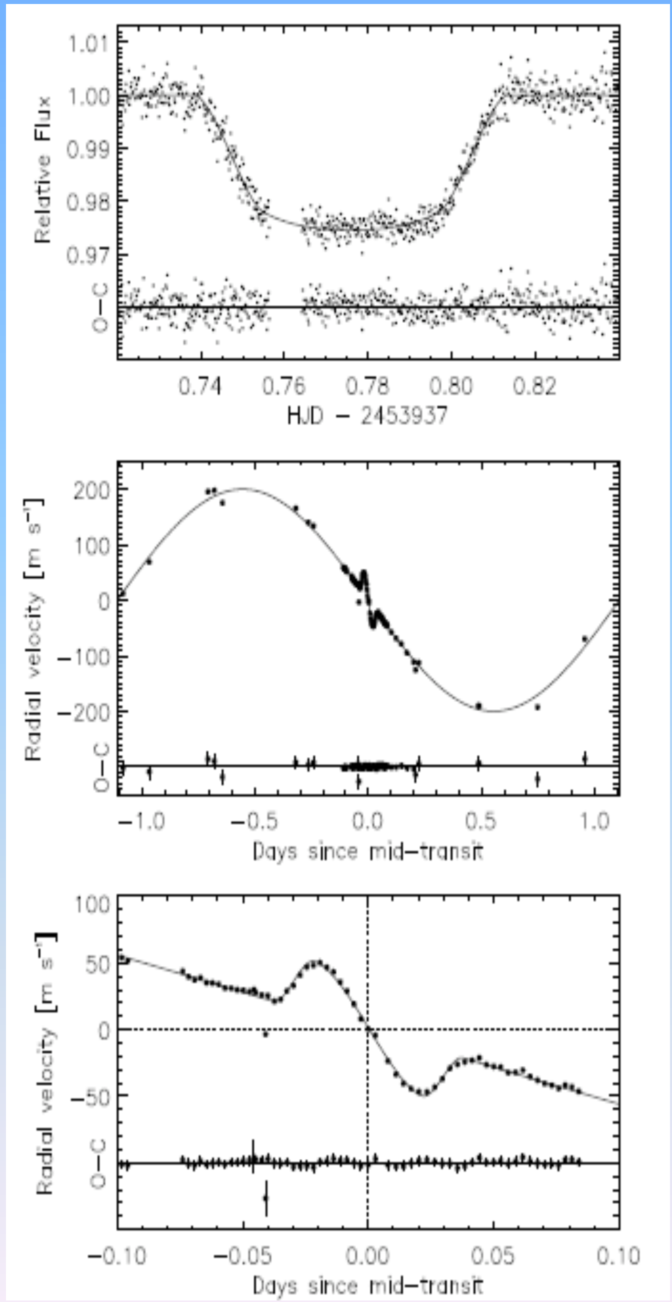


And can be used to map the planet's surface, e.g., HD189733 shows peak temperature offset from substellar point, with 972-1212K variation at 8μm (Knutson et al. 2007)

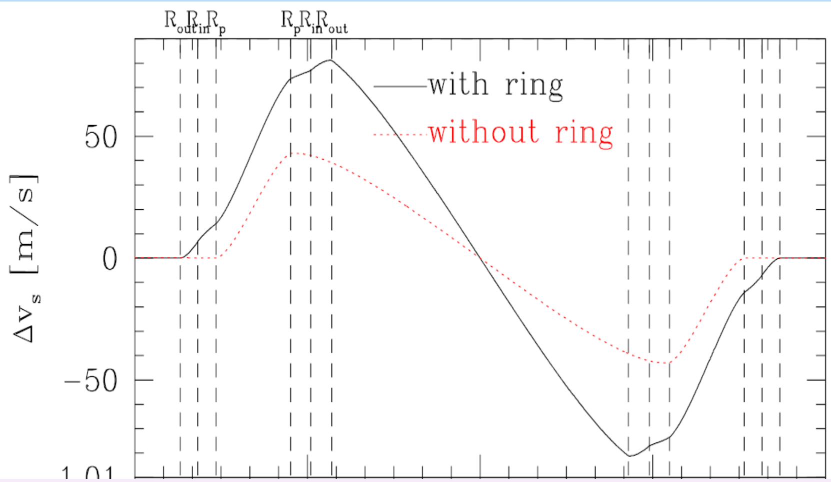
Rossiter-McLaughlin Effect

Rossiter-McLaughlin effect = anomalous doppler shift due to partial eclipse of rotating stellar surface, which can be used to measure angle between rotational axis of star and planet's orbital plane

Measured for 4 planets, with low angles (-1.4º±1.1º, -4.4º±1.4º , 14º±11º, 0±9º) -> planets orbit in stellar equatorial plane (e.g., Winn et al. 2006), although some possibly high 62º±25º (Narita et al. 2008)



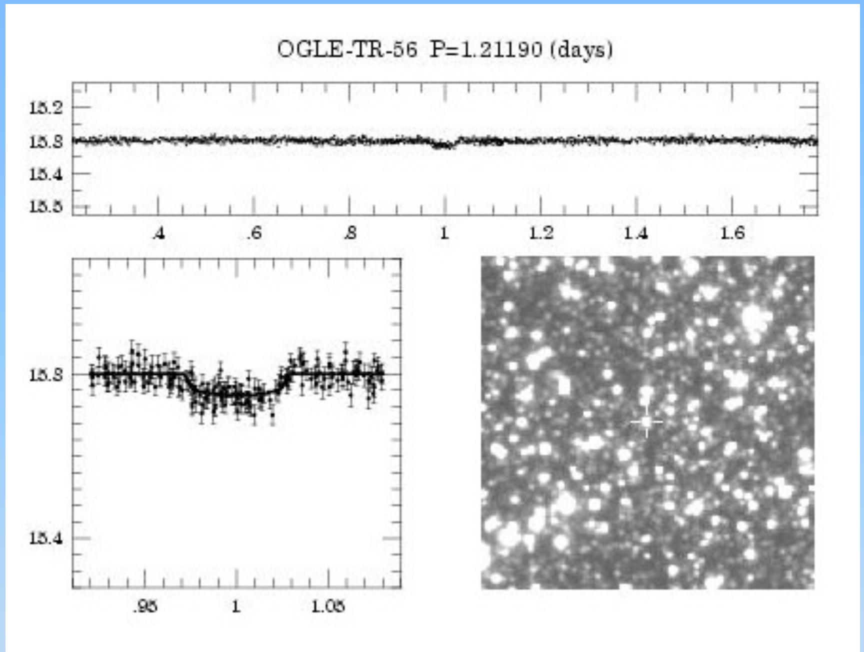
May also detect planetary rings (Ohta et al. 2007)



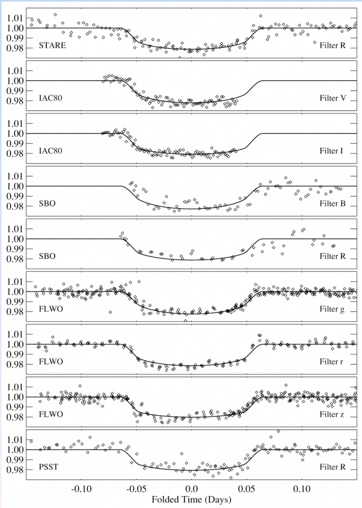
Planets discovered by transits

OGLE project monitors the light from large numbers of stars (Udalski et al. 2002)

It has detected 170 transit candidates with 6 transit planets confirmed: OGLE TR-56b, 113b, 132b, 111b, 10b (Konacki et al. 2003, Bouchy et al. 2004, Pont et al. 2004, Bouchy et al. 2005)



Other transit was detected using TrES monitoring program and confirmed spectroscopically: TrES-1 (Alonso et al. 2004) at 0.039AU, 0.75M_J, 1.08R_J -> small radius and no need for internal heat source



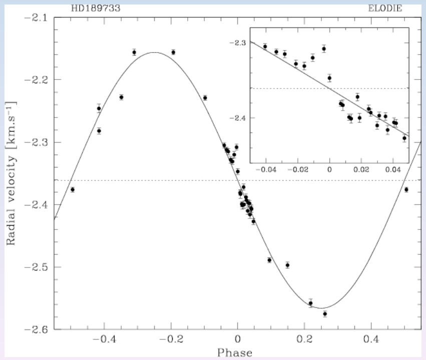
Originally thought that planets discovered by transits are closer to the star than any of the hot Jupiters?

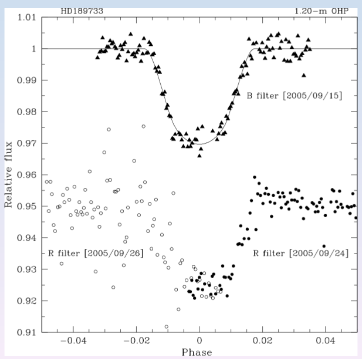
Transiting planets discovered by radial velocity surveys

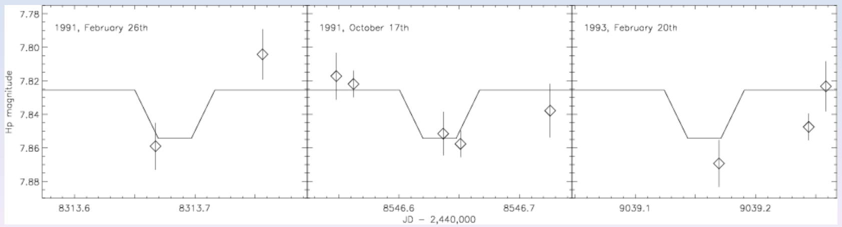
HD209458: already discussed

HD149026: G0IV with $0.36M_J$, $0.72R_J$ giving 43m/s variations and 0.3% transit (Sato et al. 2005) -> $1.07g/cm^3$ greater than predictions from insolation requiring large rocky/icy core (Charbonneau et al. 2006)

HD189733: Star very similar to HD209458 and transit detected in targeted search of high metallicity stars (Bouchy et al. 2005) -> $1.15M_J$, $1.26R_J$, $0.75g/cm^3$, a posteriori detected in Hipparcos data (Hebrard & Lecavelier des Etangs 2006) giving orbital period to accuracy of 1s ($5x10^{-6}$)





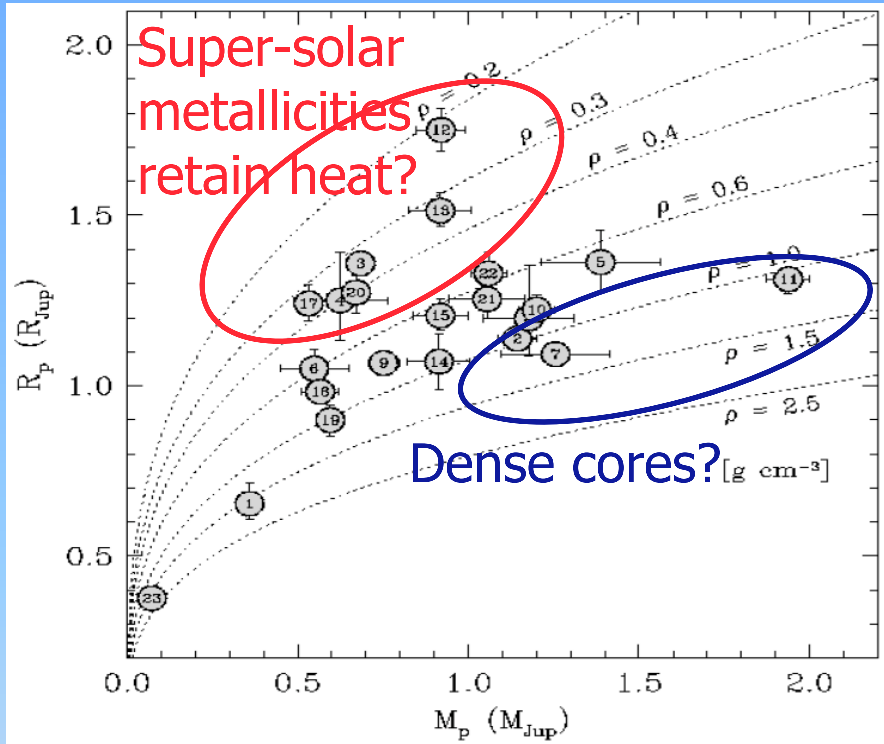


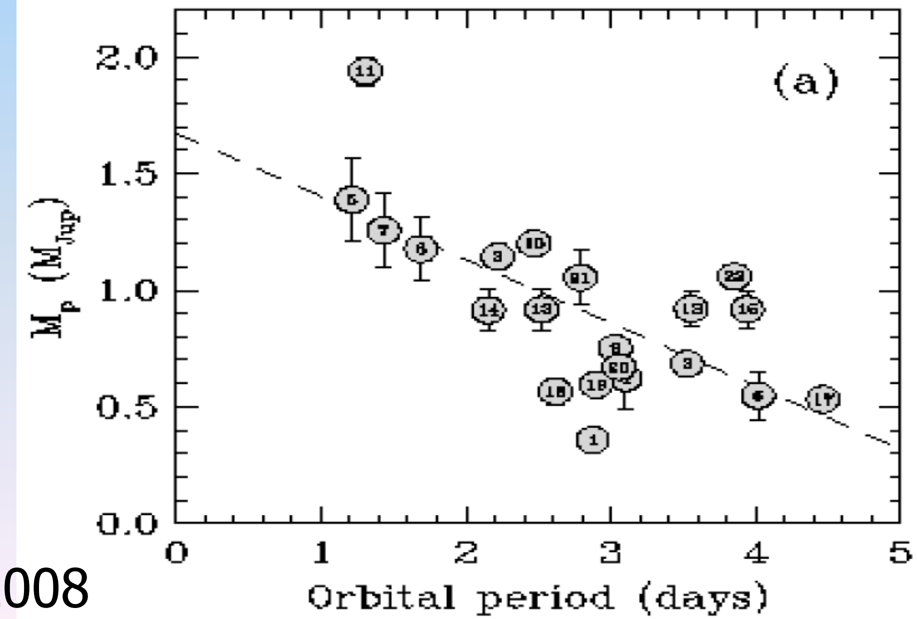
Trends from transits

We can now start looking for trends in the data with an accurate determination of M_{pl} (without sini ambiguity) and with knowledge of R_{pl}:

• Test models of core+atmospheres and stellar irradiation with mass-radius relation (Burrows et al. 2006)

• Correlation of mass with orbital period (more massive planets are closer in), perhaps caused by evaporation of planet by XUV flux (Mazeh, Zucker & Pont 2005, Baraffe et al. 2004)





Torres 2008

Ongoing transit searches/null results

Searches of globular clusters

• HST WFPC2 of 47 Tuc yielded no detections of 34,000 stars -> planet frequency order of magnitude below that of nearby stars (Gilliland et al. 2000) most likely due to low metallicity [Fe/H]=-0.7 rather than crowded environment (Weldrake et al. 2005)

Searches of open clusters/dense fields

• Hidas et al. (2005), Mochjeska et al. (2005), Kane et al. (2005), von Braun et al. (2005), Bramich et al. (2005), Street et al. (2005), Hood et al. (2005), Urakawa et al. (2006), Rosvick & Robb (2006), O'Donovan et al. (2006), Christian et al. (2006), Burke et al. (2006), Weldrake et al. (2007)

• MONITOR = (Aigrain et al. 2007, Irwin et al. 2007)

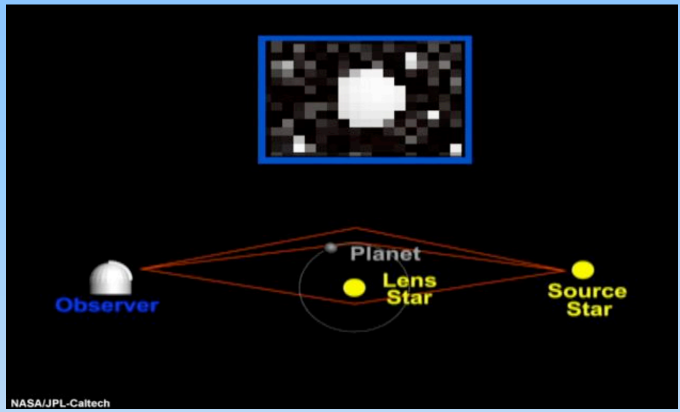
Original estimates for 200 detections/month were overestimate (Horne 2003), but field is evolving rapidly, and now getting large numbers of WASP detections and we can expect large numbers of detections from COROT/Kepler/Gaia…

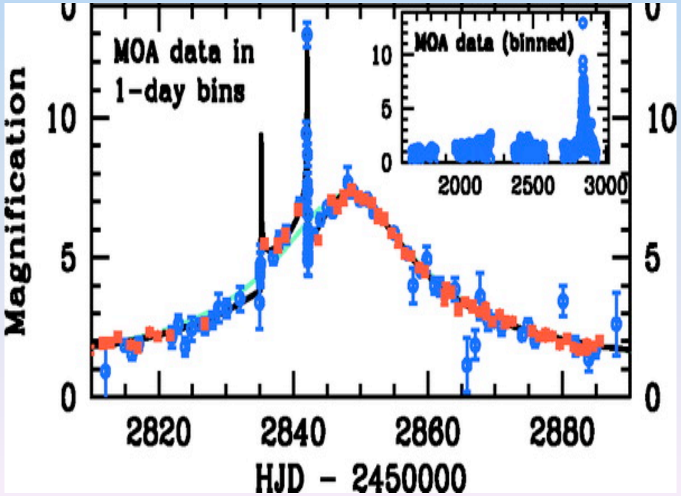
Gravitational Microlensing

Gravitational microlensing = foreground object passes close to line of sight of background source star leading to symmetric light curve profile

If the foreground lens has an orbiting planet then, if the geometry is favourable, disturbance to the light curve is possible, even for planets as small as Mars (limited by angular size of source), but requires high magnification (HM) event for source to pass over caustic

Also requires high time resolution observation of the event, so OGLE and MOA surveys have alert system for HM events (~600/yr) which are then followed up with high time sampling (PLANET/ MICROFUN)





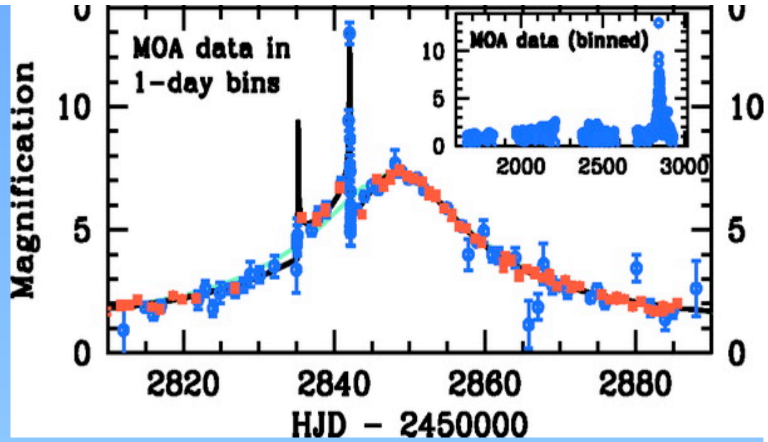
Planets Detected by Gravitational Microlensing

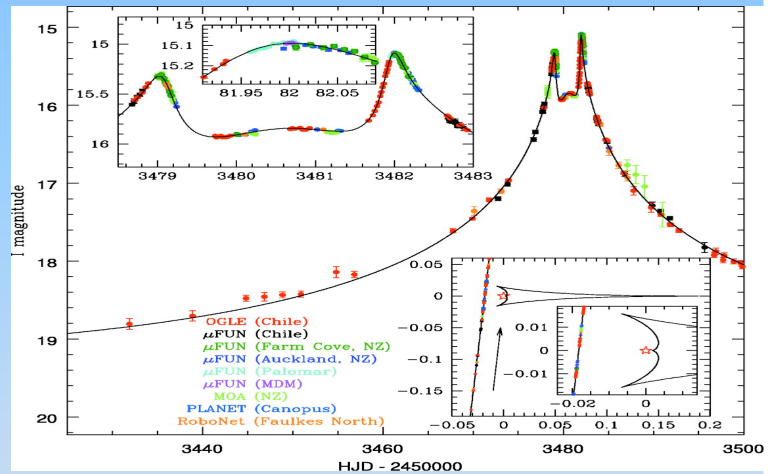
To date 7 planets have been detected by microlensing:

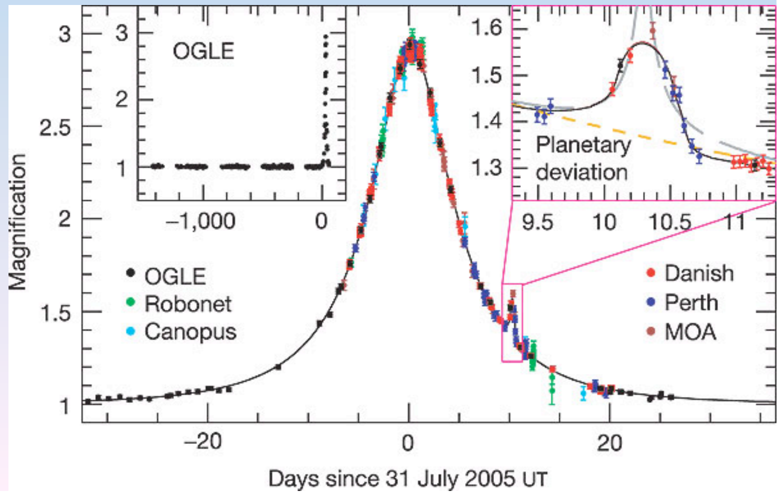
OGLE-2003-BLG-235 or MOA-2003-BLG-53: (M_{pl}/M_{*}=0.0039) 1.5M_J at 3AU from 0.36M_{sun} at 5.2kpc (Bond et al. 2004)

OGLE-2005-BLG-071: (M_{pl}/M_{*}=0.0071) 0.05-4M_J around 0.08-0.5M_{sun} at 1.5-5kpc (Udalski et al. 2005)

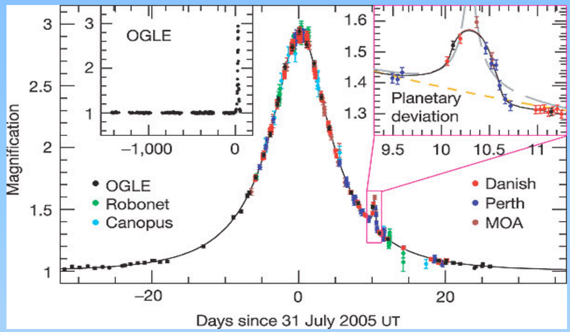
OGLE-2005-BLG-390Lb: 5.5M_{earth} at 2.6AU from galactic bulge 0.22M_{sun} at 6.6kpc lensing a G4III at 8.5kpc (Beaulieu et al. 2006)

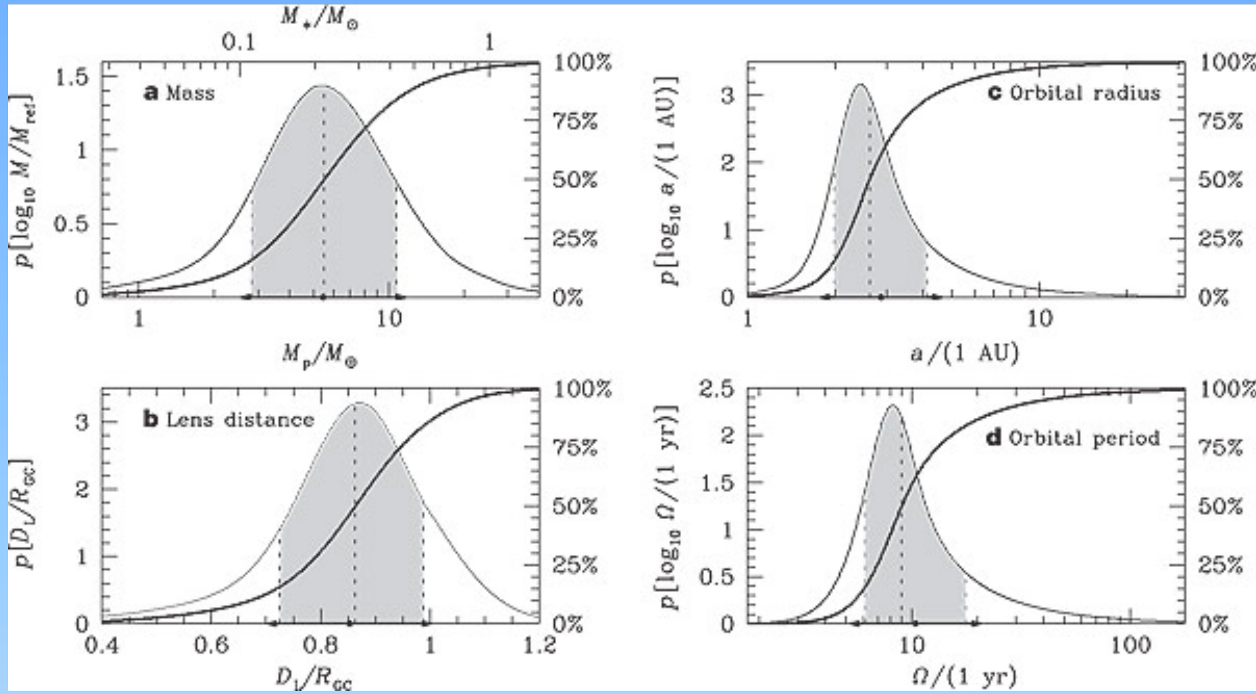






Problem with Gravitational Microlensing





The problem with microlensing planets is that properties of host star are unknown and so determined statistically from galaxy models

Follow-up hard, because host star is far away and faint, but has been achieved with HST (ACS) when proper motion moved lens away from source by 6mas (Bennett et al. 2006, 2007)

They can however detect Earth like planets (Park et al. 2006) and can be used to set statistical limits on the frequency and properties of such planets: e.g., Gaudi et al. (2002) show that <45% of M dwarfs have >3M_J at 1-7AU

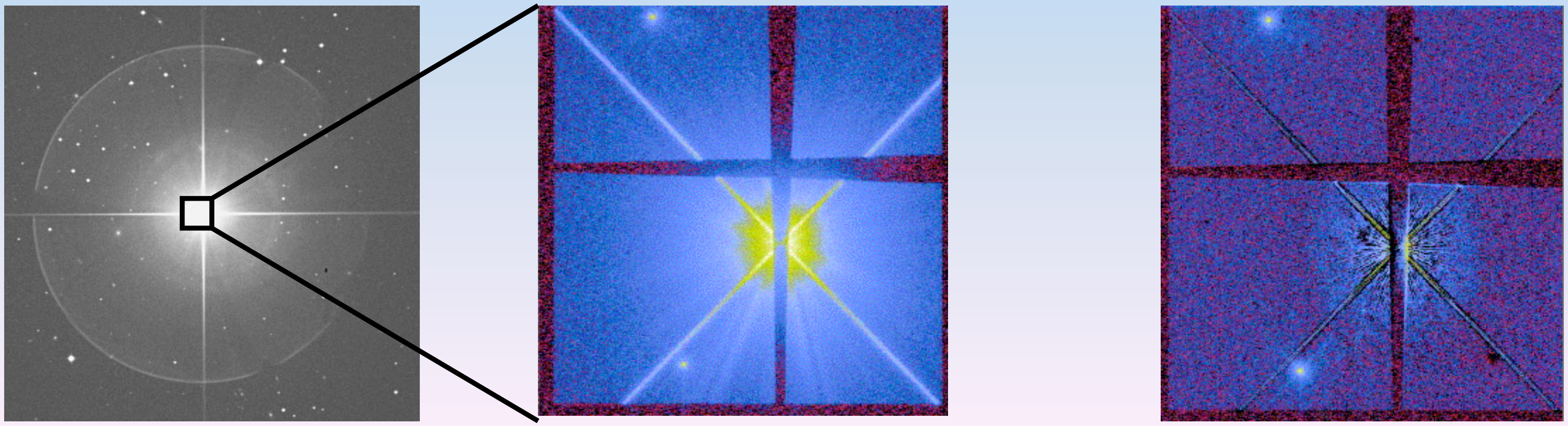
Direct Imaging of Planets: Techniques

The problem with directly imaging a planet is that it is near a bright star. Thus techniques have been developed to circumvent that problem:

- Coronagraphy
- Extreme Adaptive Optics or LUCKY imaging to remove atmosphere (MacKay at IoA)
- Interferometry and nulling interferometry (Langlois et al. 2006)
- Choosing to look for planets with relatively high flux

Most techniques regularly get down to 2-3M_J limits at >10s-100s of AU, but that is getting better

Take a star… …block out its light… … and remove residuals



Direct imaging of planets: false alarms

Direct imaging of planets also suffered from false alarms at the start:

NICMOS images of TMR-1, a binary (42AU) protostar in Taurus showed a faint companion at 10” (1400AU) at the end of a long filament consistent with a young planet of 2.5-15 M_J possibly recently ejected from proto-binary (Tereby et al. 1998)

However, later observations showed this is too hot to be a proto-planet and is more likely a background star at 2.5kpc behind the Taurus cloud (Tereby et al. 2000)

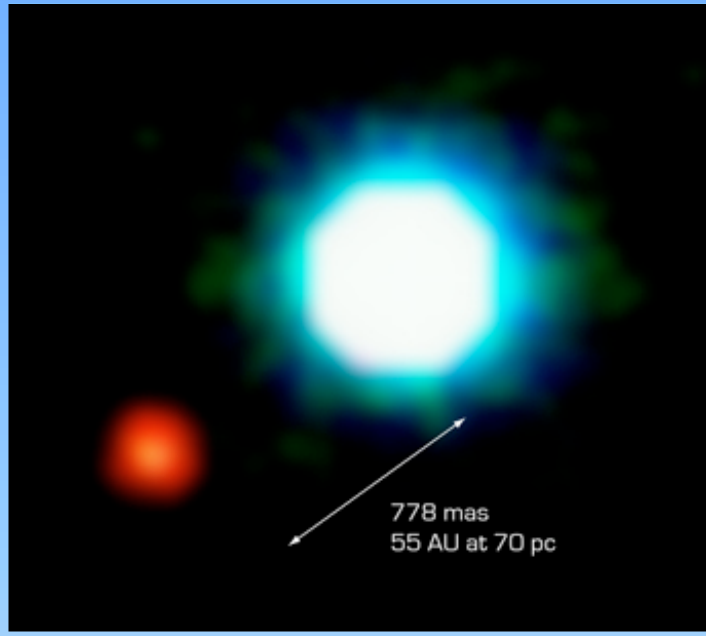
Direct imaging of planets

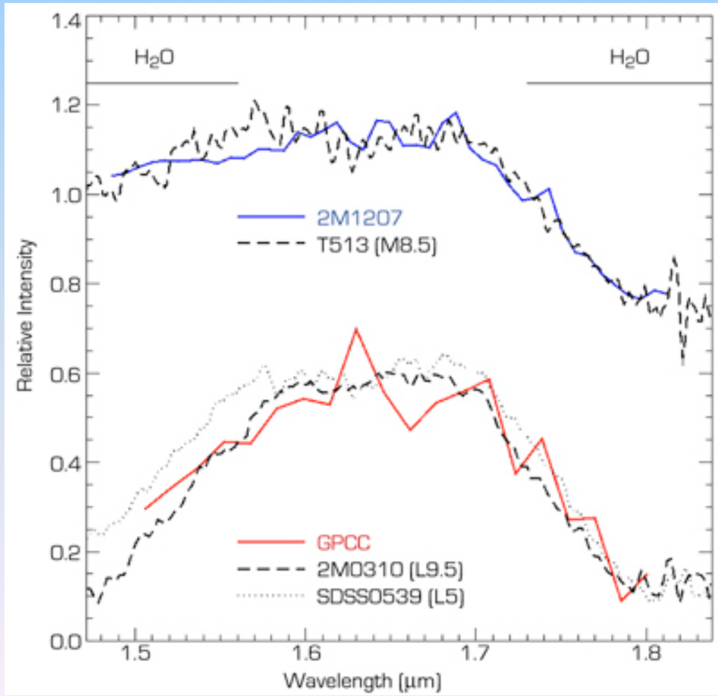
The first planet to be imaged was that around the brown dwarf 2MASS 1207334-393254 using the NACO adaptive optics system on VLT (Chauvin et al. 2004)

Planet: 3-4M_J (confirmed with spectroscopy to be late L-type) at 55AU projected separation
Star: brown dwarf (M8.5) 21M_J at 53pc (Mamajek et al. 2005)

Imaging was possible because:

- the system is young – 8Myr (member of TW Hydra moving group), which means the planet is relatively bright (Burrows et al. 1997; Baraffe et al. 1998)
- the star is faint (planet is only 100 times fainter than star)



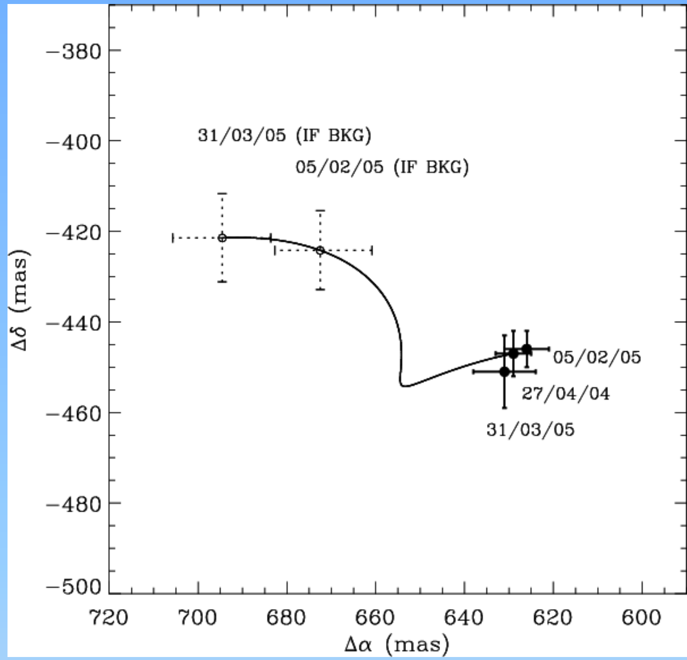


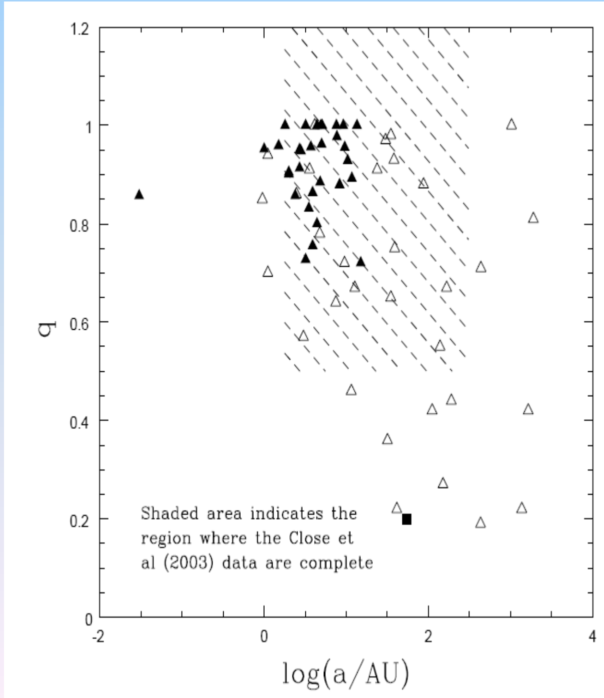
Origin of 2MASS1207 planet

The planet was confirmed to be a companion to the brown dwarf using multi-epoch imaging (Chauvin et al. 2005)

The most important question is its origin:
• Binary: mass ratio is ~0.2 and semimajor axis is 55AU, which is not unlike companions to G-type stars, but BD binaries have tendency toward equal mass ratio and <15AU orbits (e.g., Lodato et al. 2005)
• Formation in disk through core accretion, gravitational instability
• Capture?

It's also important that both objects are surrounded by dust disks (Mohanty et al. 2006), although low luminosity interpreted as hot protoplanet collision afterglow (Mamajek & Meyer 2007)



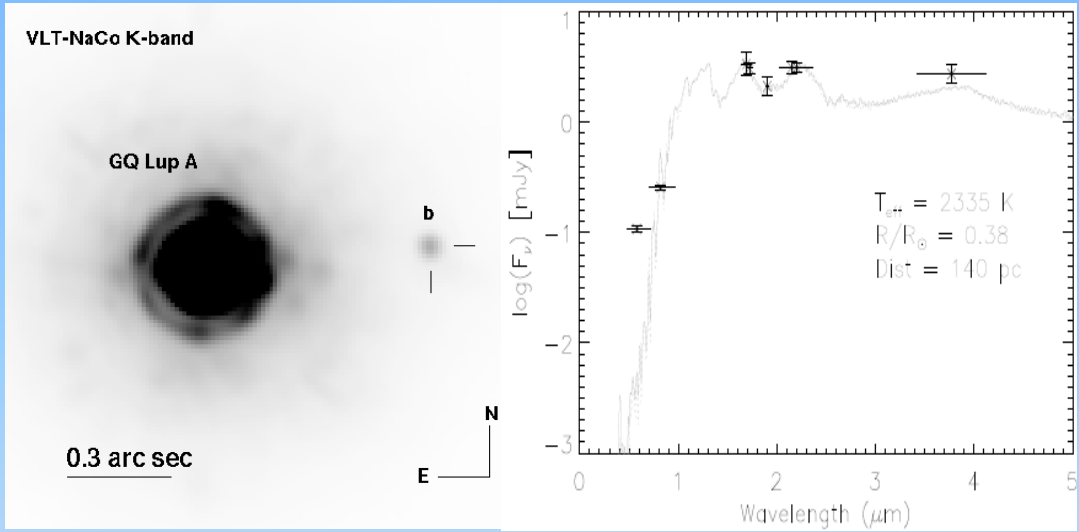


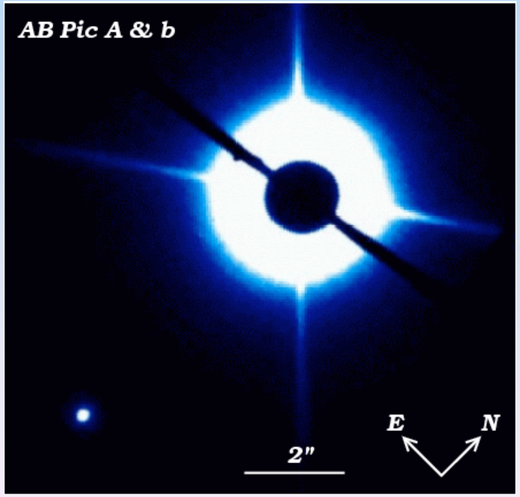
Other imaged planet companions

Two other young late-type stars have also been found to have companions:

GQ Lup: 0.7M_{sun} K7eV a 0.1-2Myr in Lupus with a 10-20M_J companion at 98 AU, high H_α indicates possibly still accreting (Neuhauser et al. 2005; Seifahrt et al. 2006; Marois et al. 2007; McElwain et al. 2007)

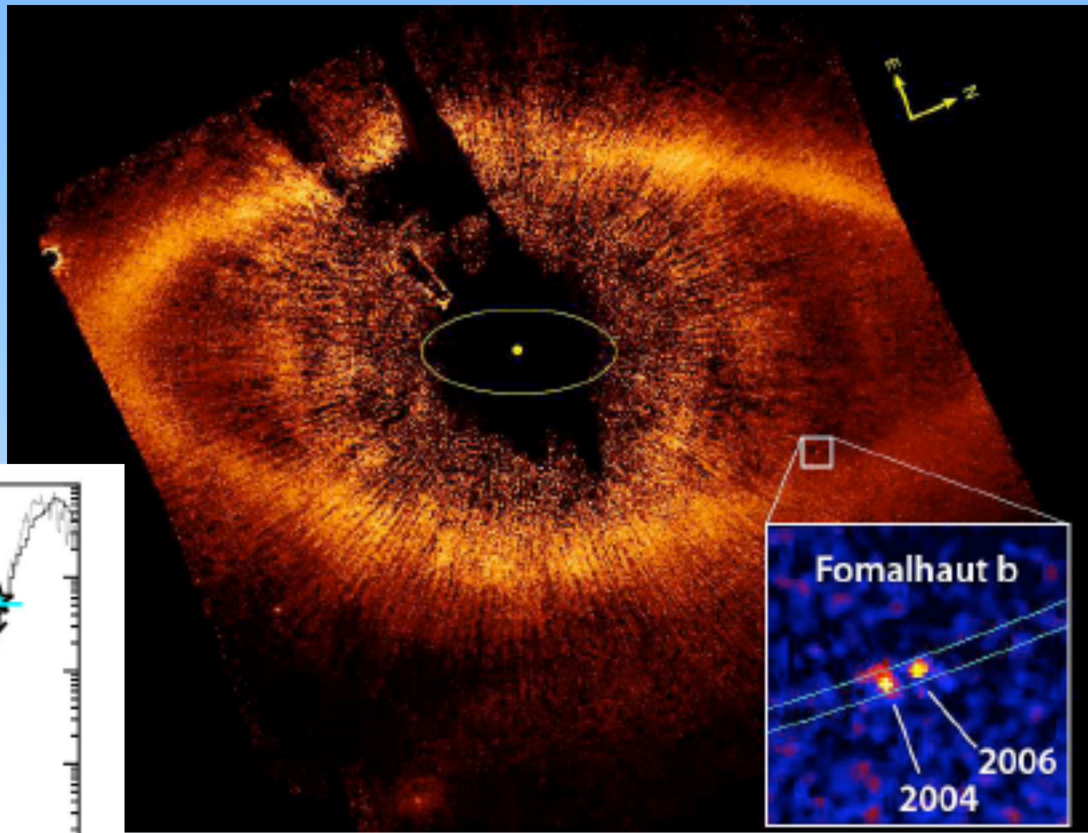
AB Pic: K2V at 47pc a 30Myr in Tucana-Horologium association with 13-14M_J companion at 260 AU (confirmed spectroscopy and proper motion, Chauvin et al. 2005)

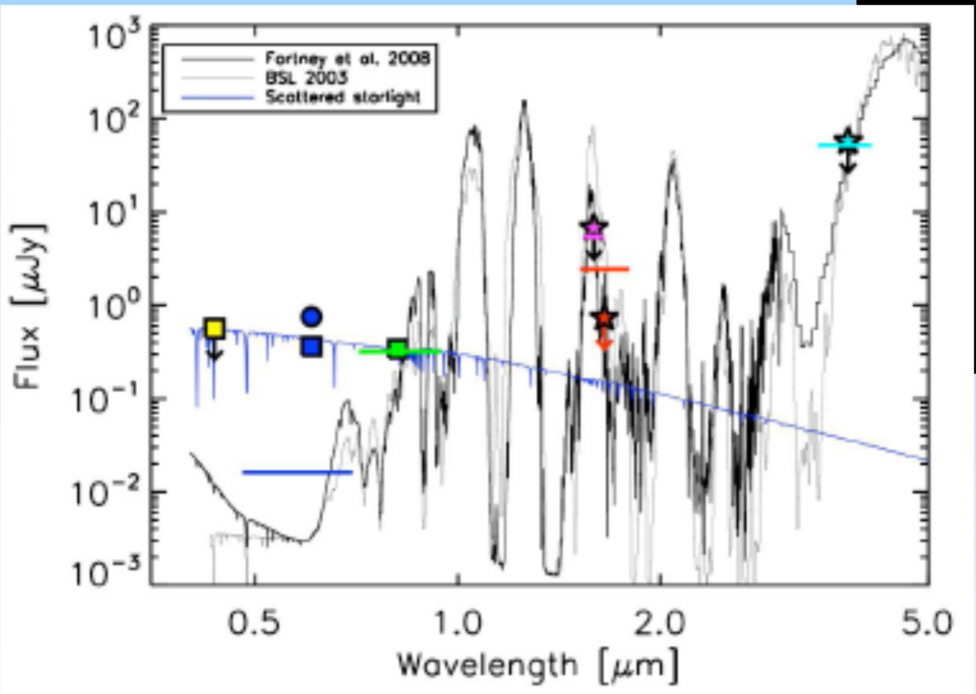




Recently imaged planet companions

Fomalhaut planet imaged at inner edge of debris disk (Kalas et al. 2008)

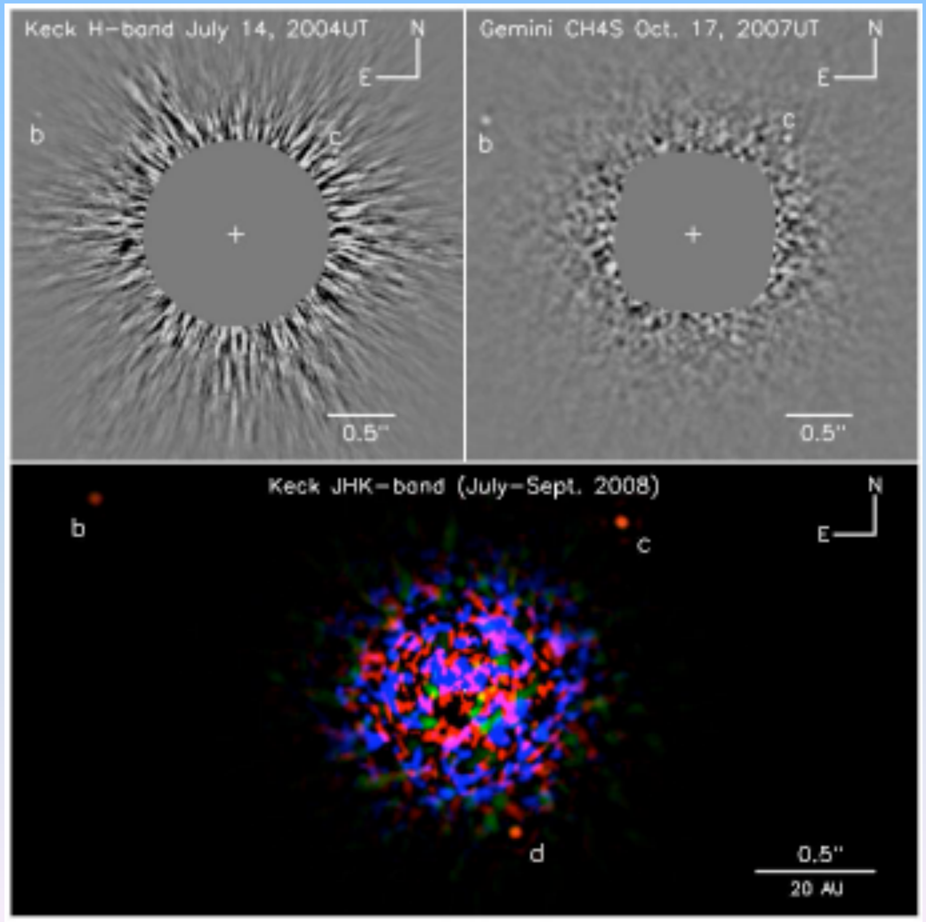




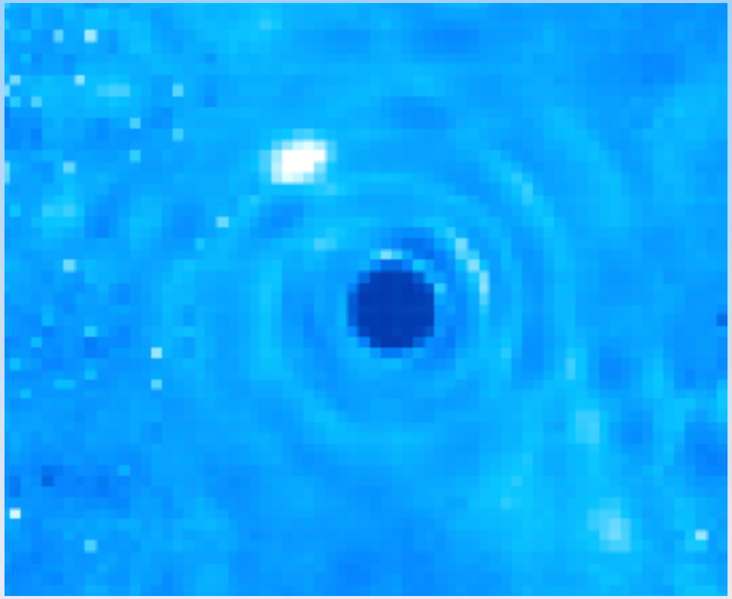
Emission spectrum possibly indicative of circumplanetary disk; unexplained variability

Recently imaged planet companions

Three planets imaged around HR8799 (Marois et al. 2008)



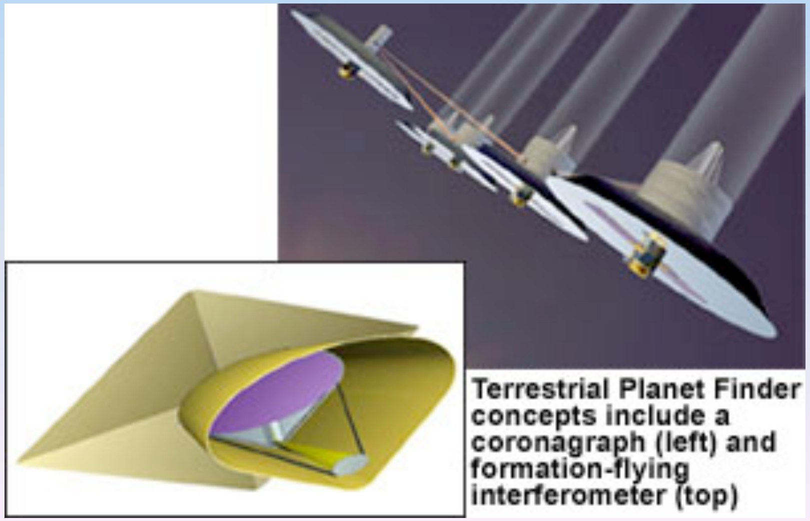
Probable planet imaged to beta Pic edge of debris disk (Lagrange et al. 2008), but see also Boccaletti et al. (2008) for different epoch observations



Future of direct imaging

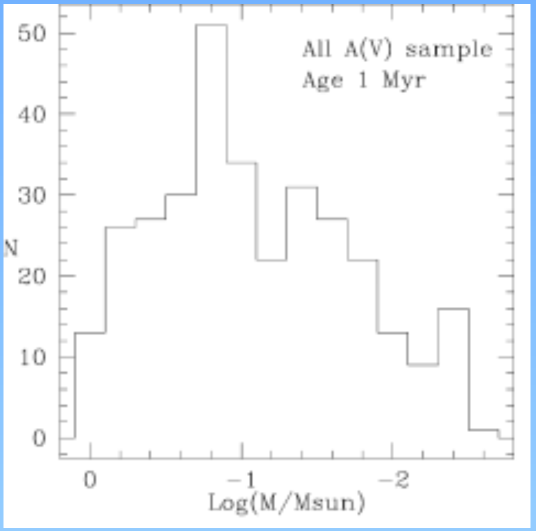
ELT from ground (Gilmore at IoA)
• 100m telescope can detect Earth-like planets but lots of technical challenges to e.g., the AO system to get noise under control: Chelli et al. (2005), Cavarra et al. (2006)

Darwin/TPF from space (Beichman/Fridlund, White in UK)
• Coronagraphic imager (US)
• Mid-IR interferometer (contrast ratio is better planet/star in mid-IR, Europe) (e.g., Mennesson & Marrioti 1997)



Terrestrial Planet Finder concepts include a coronagraph (left) and formation-flying interferometer (top)

Free-floating planets



There is now evidence for a substantial population of what are known variously as free-floating planets, planetary mass candidates, sub-stellar objects, mostly discovered in surveys of star forming regions (e.g., Lucas et al. 2005)

They have masses below the deuterium burning limit (formally the IAU recognises objects below 13.6M_J as substellar) but are not orbiting a more massive star; they can be a small as 2M_J

What we call them is a semantic issue; the real question is did they form like stars by turbulent fragmentation (Padoan & Nordlund 2002), disc instability, were originally more massive (Whitworth & Zinnecker 2004) or are they ejected planets (Reipurth & Clarke 2001)

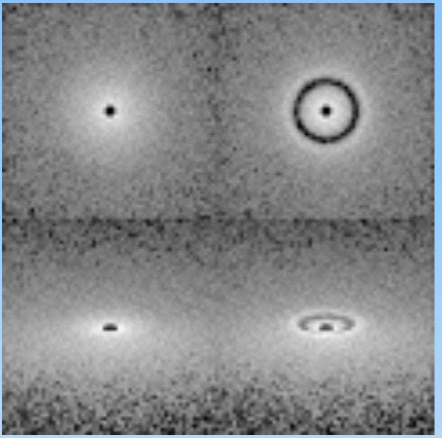
Constraints from binary fraction, mass distribution, presence of disks (e.g., Luhman et al., 2005)

Other planet detection techniques

Disk structures

• Planets carve a gap in a protoplanetary disk which could be detectable in direct imaging e.g., with ALMA or in the spectral energy distribution (e.g., Varniere et al. 2006)

• Planets impose non-axisymmetric structure on disks (e.g., Wyatt 2008)

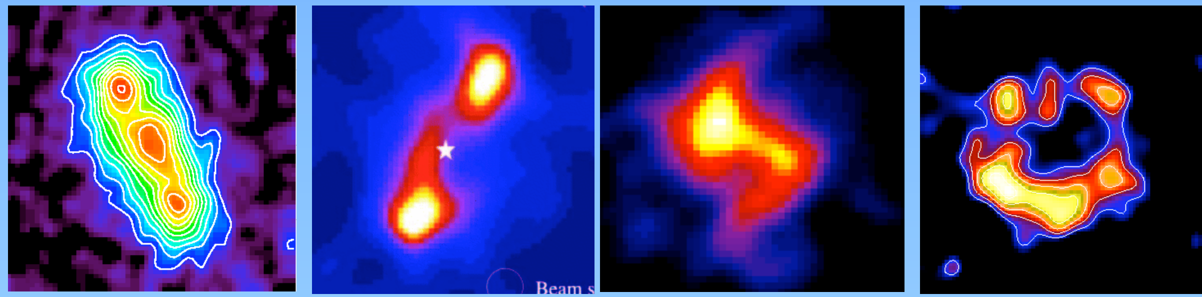


Other

• Radio emission from extrasolar planets (Zarka 2004; Farrell et al. 2004; Winterhalter et al. 2005; George & Stevens 2007; Greißmeier et al. 2007; Smith et al. 2009)

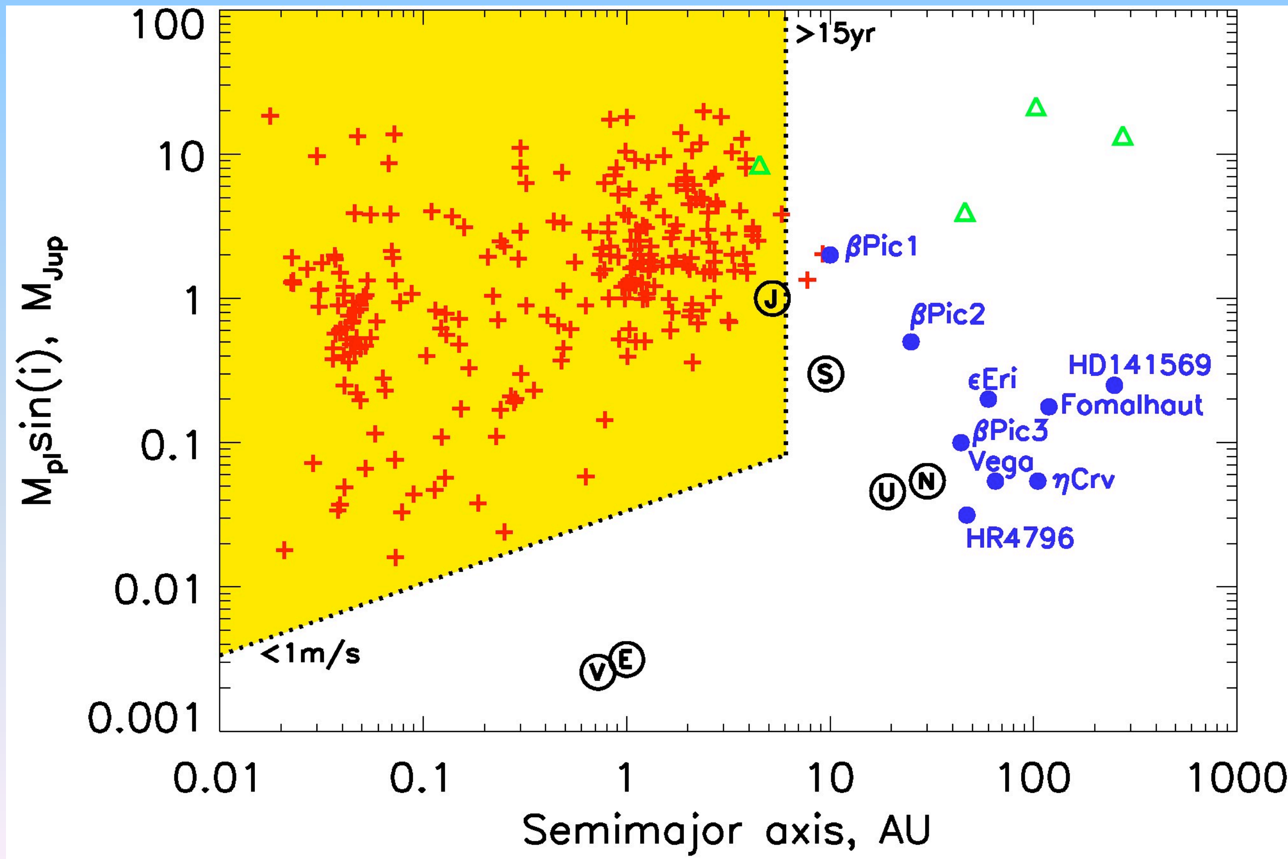
Structure in Debris Disks

Debris disks imply >km planetesimals around main sequence stars, but also evidence for planets:



• inner regions are empty, probably cleared by planet formation

• disks are clumpy/ asymmetric, probably caused by unseen equivalent of Neptune



Planets are lower mass and further out than those detected with other means