Topics in Astrophysics

Michaelmas Term, 2010: Prof Craig Mackay

Module 10: Exoplanets

- Our Solar System, discovery methods for exoplanets,
- The pulsar planets, exoplanets orbiting main sequence stars.
- Range of masses and orbits observed.
- Star formation and planet formation.
- Hot Jupiters.
- Proto-planetary discs, forces on dust grains
- The importance of metalicity, the Hill radius, future prospects.

1

Extra-solar planets (exoplanets)

- These are planets not in orbit around the sun.
- No strict definition to distinguish low mass stars from planets but basically they have low mass (<13 M_J) and are formed in the disk of debris left over from the formation of a star.
- >13 M_J are called brown dwarfs irrespective of how they were formed.
- Over 490 exoplanets now known (late 2010) and ~5% of solar-type stars have a massive (> 0.5 M_J) planet.
- Very exciting new field of astronomy.
- Ultimately wish to know how many Earth-like planets there are and how common life is in the universe.

2

Our solar system

- For comparison purposes let us consider the basic facts about our own solar system. (Before 1991 we had no observational evidence of any planets outside our solar system).
- 99% of the mass of the solar system is in our Sun with a mass of $2x10^{30}$ kg. Our Sun is a main sequence star of type G2V with an effective temperature, T ~ 6000K.
- The mass in our planetary system is very much less than the mass in our central star, the Sun. There are eight planets (Pluto was recently demoted).
- The planetary system is concentrated in a thin disk with orbits that range from 0.4 to 30 AU. The orbital sizes follow Bode's law (each orbit is ~1.71 times bigger than the one inside it).
- The angular momentum of the solar system is almost entirely contained in the orbits of the planets (mostly of Jupiter and Saturn).
- The orbits are fairly close to circular.
- At distances < 2 AU there are four high-density rocky planets whereas at distances > 5 AU the other four planets are low-density gas giants.
- Useful mass numbers: Jupiter is 0.001x solar mass, Earth is 0.003x Jupiter mass.
- Do we believe that our solar system is unique? Do we have any evidence that what happened to create our solar system might have happened elsewhere and created other planetary systems?

3

Exoplanet Discovery Methods

- **Direct high resolution imaging [>4](take a picture)**
- Dynamical perturbations (see a wobble)
  - **Radial velocities [>300]**
  - Astrometry
  - **Pulsar timing [>4]**
- Variations in total light (see a blink or a flash)
  - **Transits [~3500]**
  - Reflections
- **Micro-lensing [>100](see a flash)**
- Finding gas disk gaps and warps due to planets.

Numbers in [] brackets indicate number found by that method (and all numbers increasing all the time).

- Now (2020) radial velocity and transit techniques completely dominate the discoveries.

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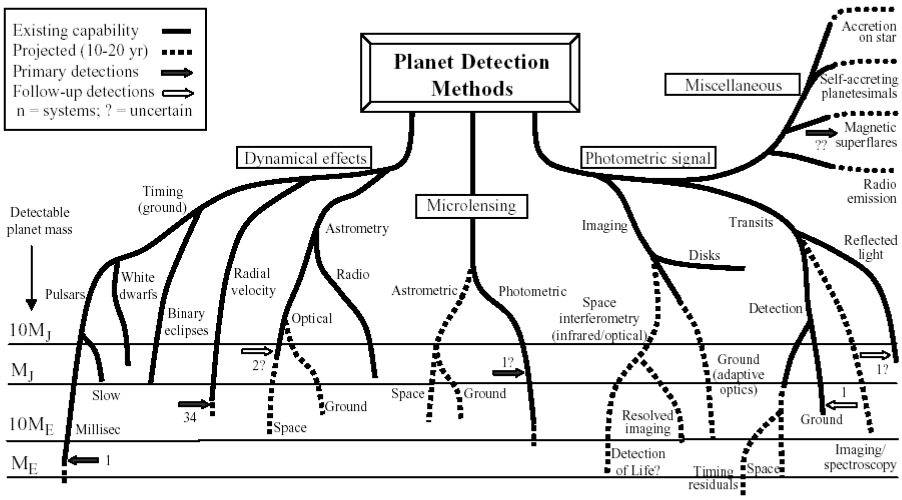
Exoplanet Detection Methods



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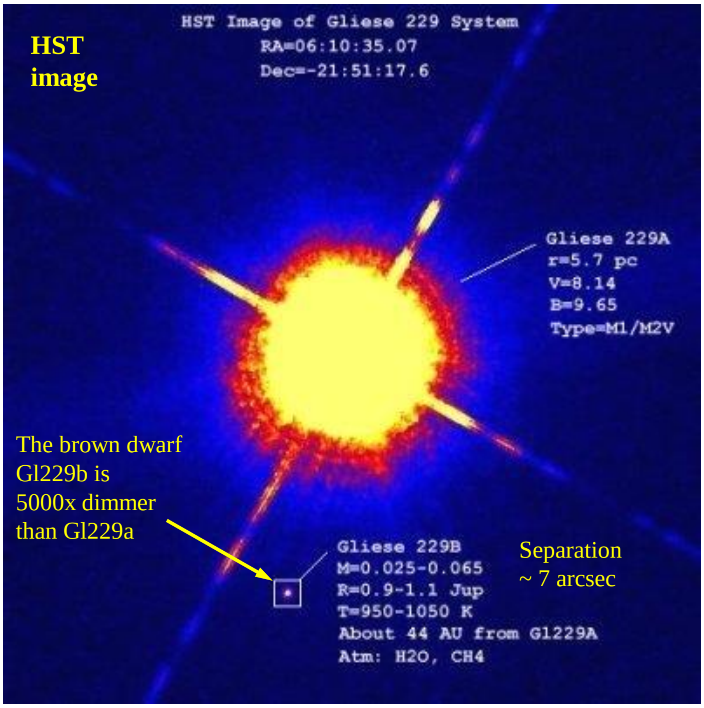
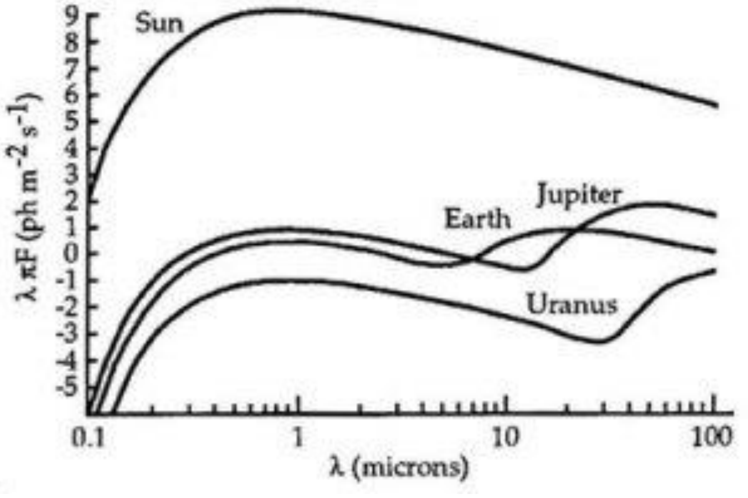


Imaging exoplanets: the contrast and proximity problems

At 10 pc a Jupiter-sized planet would appear 14 times closer and 200,000 times dimmer than Gl229b!

Contrast is better in the infra-red



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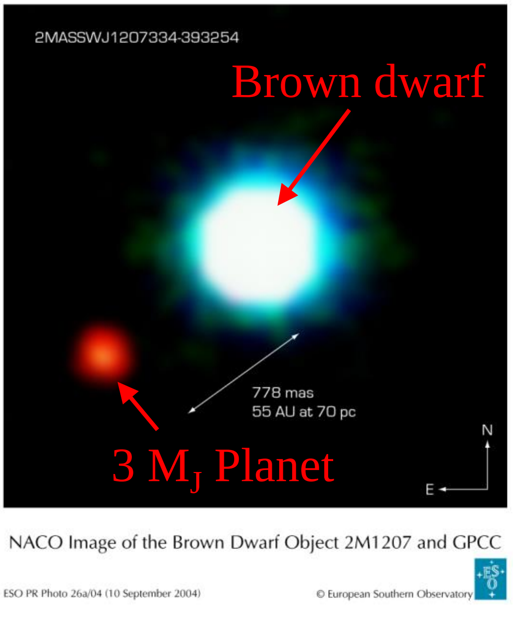
A direct image of a planet.

Revised distance estimate

53pc away
41AU separation



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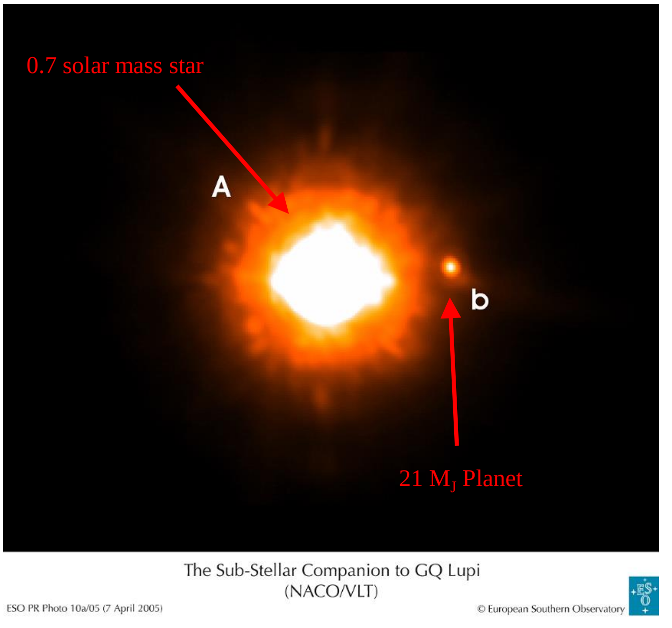
A direct image of a plane.



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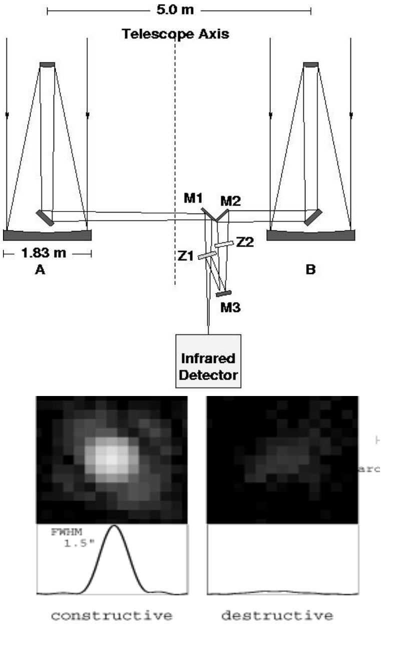
Extra Solar Planets: Direct Detection

- Nulling interferometry uses two telescopes where the light is brought together to interfere constructively and produce Michaelson interference fringes.
- By selecting the spacing of the two telescopes it is possible to adjust the fringe spacing on the sky.
- The trick is to select a fringe spacing that gives the first minimum from the central star coincident with the central maximum of the planet. Remember that we can choose a star for which we already have an indirect detection and so we have some idea where to expect the planet's image to be.
- The diagram opposite shows the arrangement and it also shows the effect on the central star image that this arrangement has.
- In this way it is possible to reduce the contrast ratio by a factor of about a hundred which is the best that one is generally able to do with interferometry from the ground.
- By using this method in the near infrared it should make it possible to detect planets directly provided each telescope has itself got diffraction limited imaging, something that will usually require adaptive optics to make it work from the ground.



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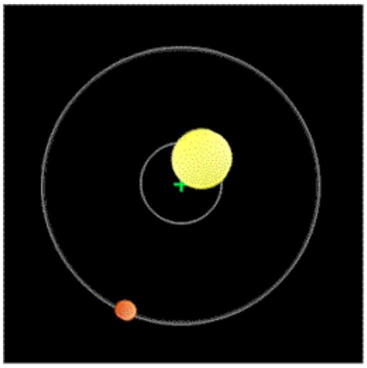
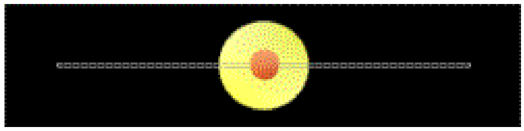
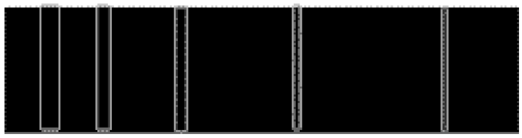
Detecting planets



Astrometry
(wobbling)

Photometry of transit (winking)

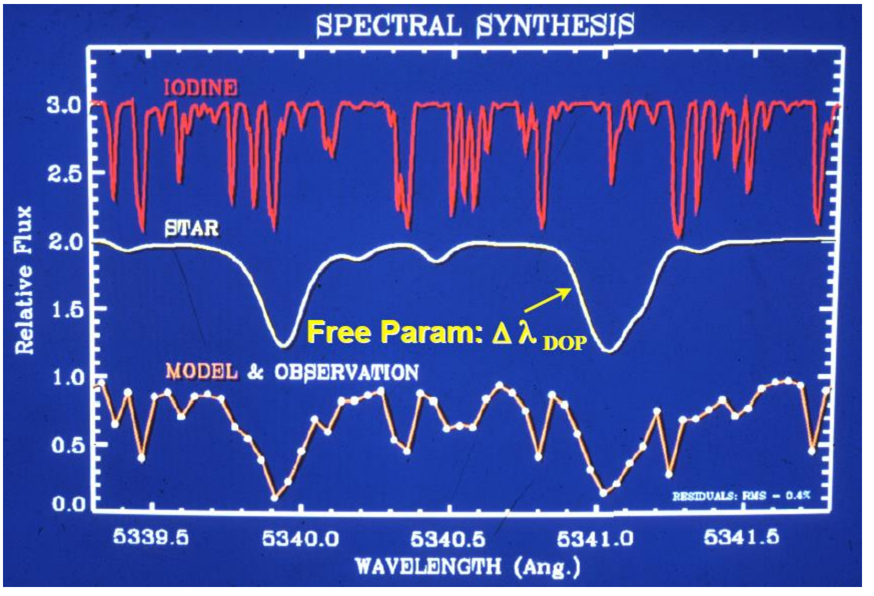




Doppler shift of spectrum (warbling)

Measuring Radial Velocities

- Require a precision of ~1 m/s.
- For example, the reflex motion of the Sun due to Saturn is about 3 m/s.
- Use an Iodine cell in the light path to provide an ultra precise wavelength reference.
- Use a spectrometer with a very high spectral resolution R=100,000=λ/Δλ.
- Need stability over many years (>10).



Slide credit: Geoff Marcy

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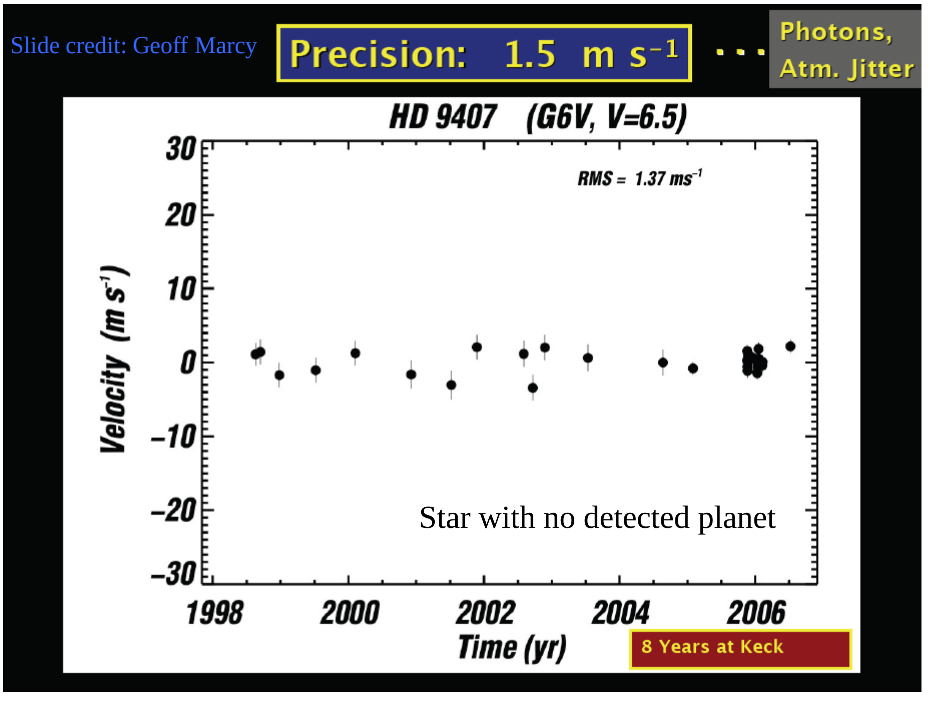
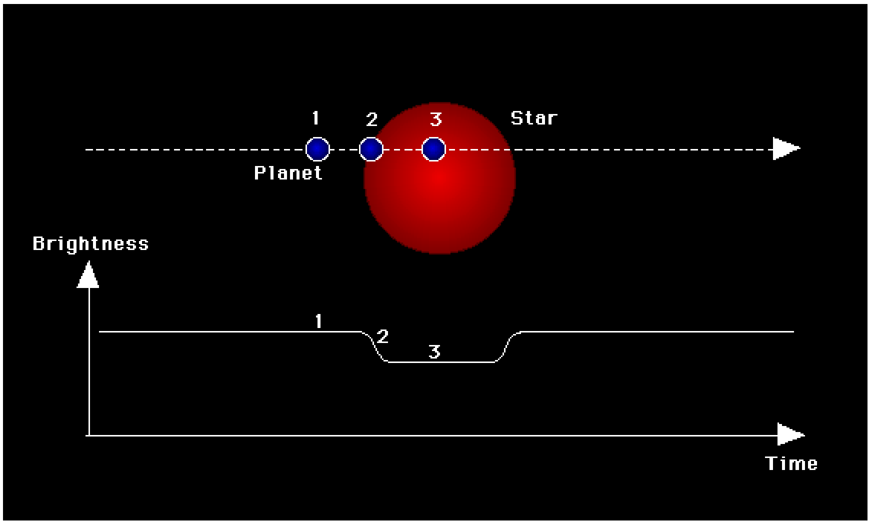


Detecting planets via transits



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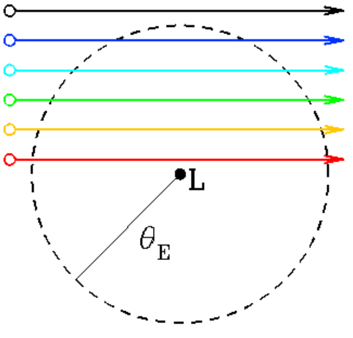
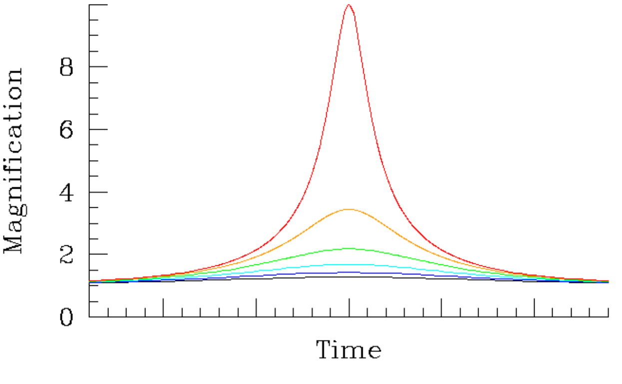


Micro-lensing
Light curves for a background star being lensed by a foreground one

Signal is proportional to the total area of the images →



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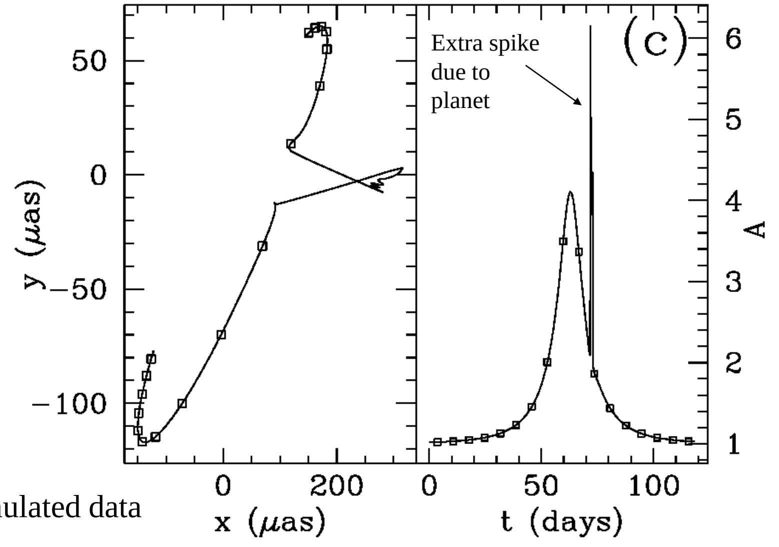
A planet orbiting the lensing star can significantly alter the light-curve



Simulated data

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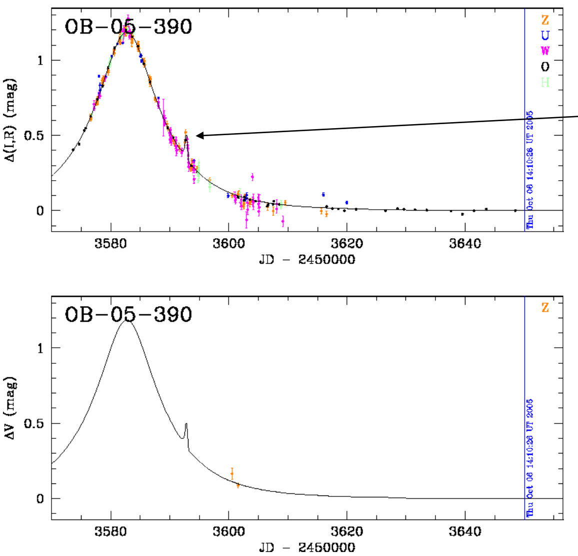
A planet orbiting the lensing star can significantly alter the light-curve



Extra spike due to planet

Real data!

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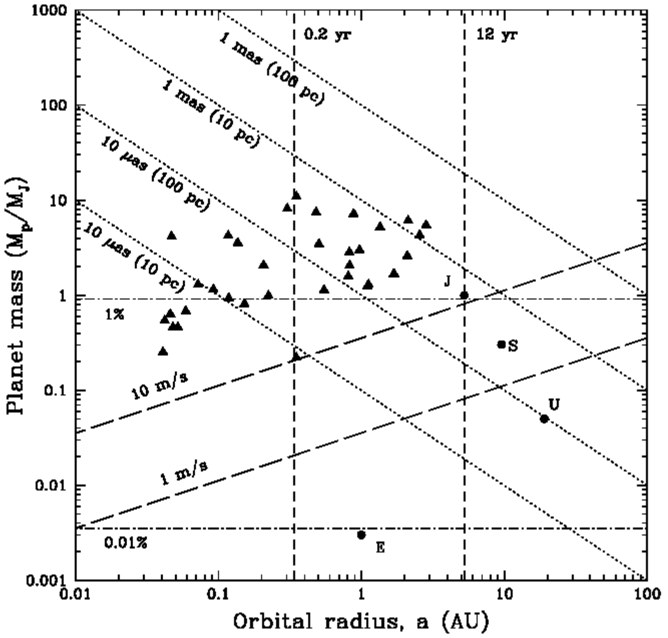

Detection methods

- Parent star is one solar mass.
- Horizontal lines are for transits.
- +ve slope lines are for radial velocities.
- -ve slope lines are for astrometry.
- Very long and very short periods are harder to detect (vertical lines).
- In summary, there are serious selection effects.

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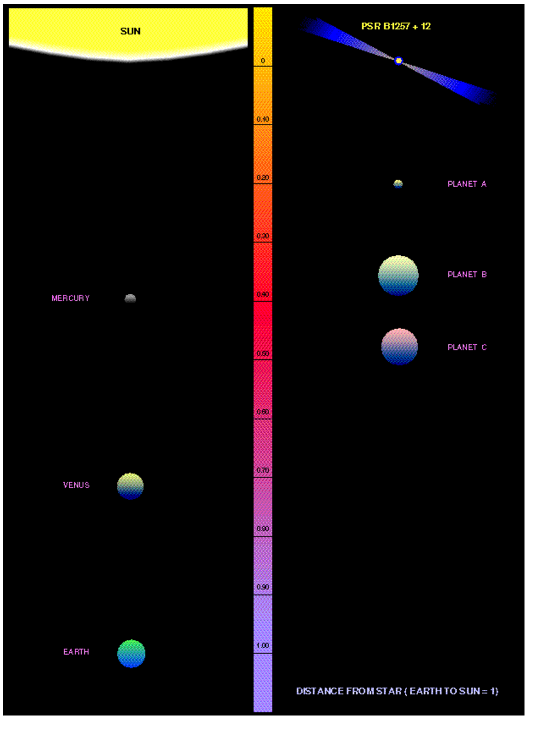
First exoplanets discovered

- In 1991 Alexander Wolszczan discovered planets orbiting the pulsar PSR1257+12.
- This pulsar gives off ~160 pulses per second and their arrival times can be measured with great accuracy. It is a spun-up milli-sec pulsar.
- Periodic departures from the expected arrival times revealed 3 planets
- 2 are as massive as the Earth and one is as massive as the moon.
- No other pulsar planets have been detected.



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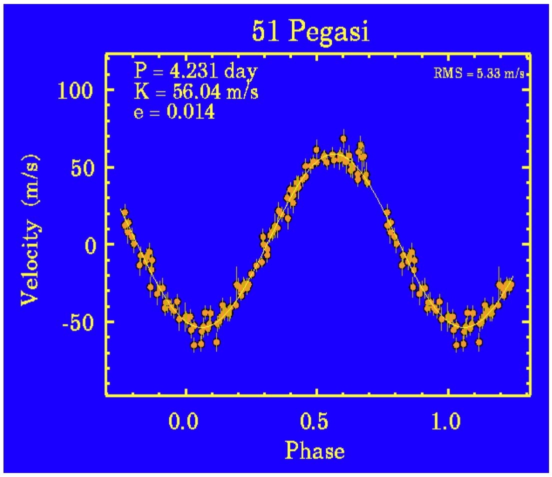
Exo-planets orbiting normal stars

- The first one was discovered in 1995 by Queloz and Major and it orbits the star 51 Peg.
- Today (late 2010) over 490 confirmed exoplanets are known and the majority have been discovered via the radial velocity technique (orbiting solar-type stars).
- Transit method is starting to produce many candidate planets. e.g. OGLE-III project has reported ~100 such candidates. ~14 transit candidates have now been confirmed.
- Searches find many Jupiter-sized planets in small orbits. ("Hot Jupiters")



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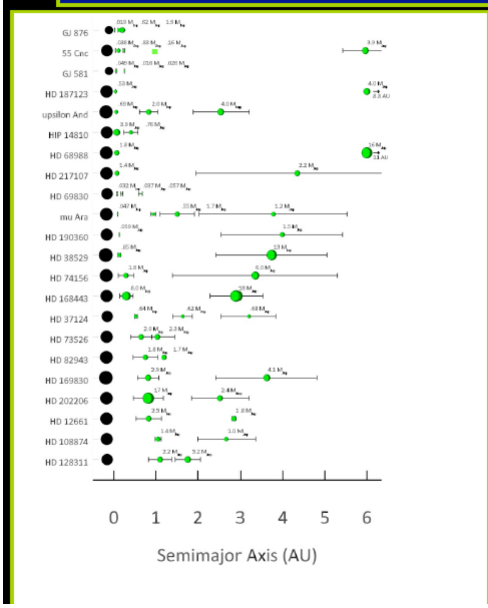
22 Multi-Planet Systems



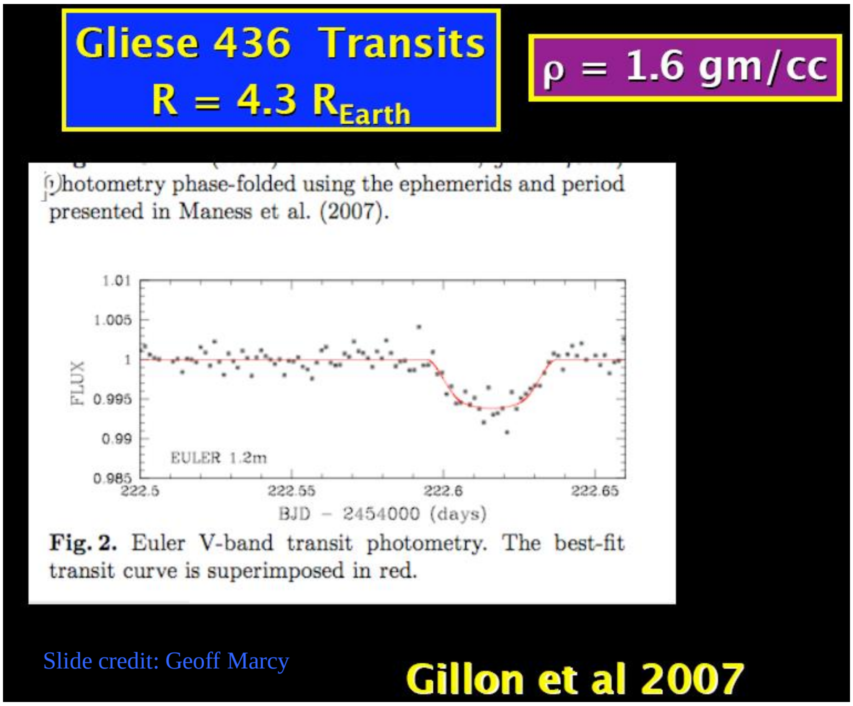
- 4 2:1 Mean-Motion Resonances

Gl876, hd82943, hd128311, hd73526

Implies:

- Orbital Migration
- Capture into Resonances
- Eccentricity Pumping

Slide credit: Geoff Marcy


Gliese 436 Transits
R = 4.3 R_{Earth}
ρ = 1.6 gm/cc
photometry phase-folded using the ephemerids and period presented in Maness et al. (2007).
FLUX
EULER 1.2m
BJD − 2454000 (days)
Fig. 2. Euler V-band transit photometry. The best-fit transit curve is superimposed in red.
Slide credit: Geoff Marcy
Gillon et al 2007

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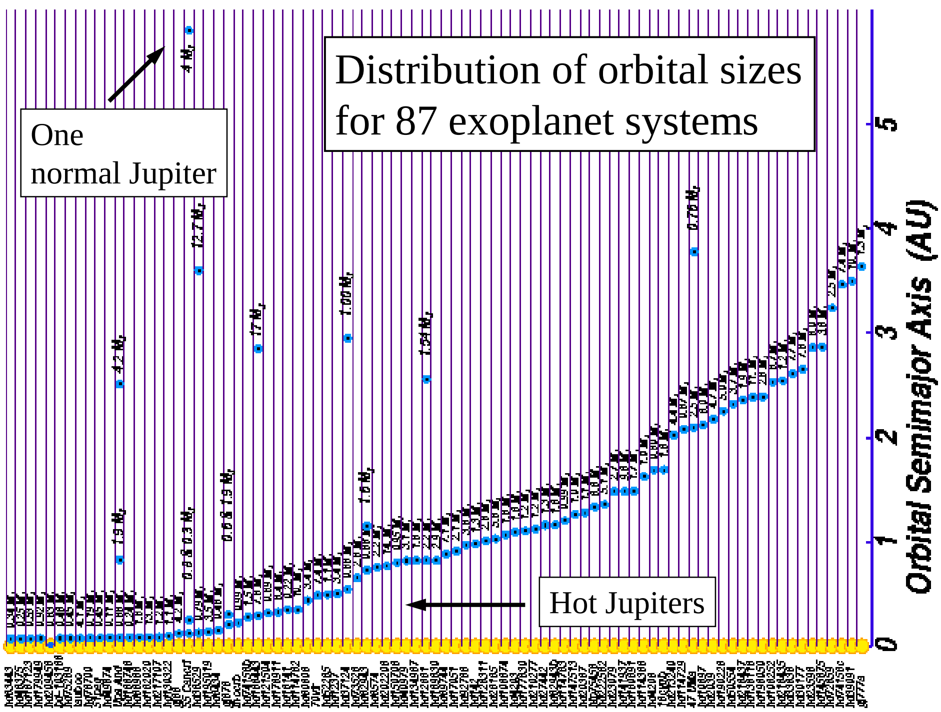
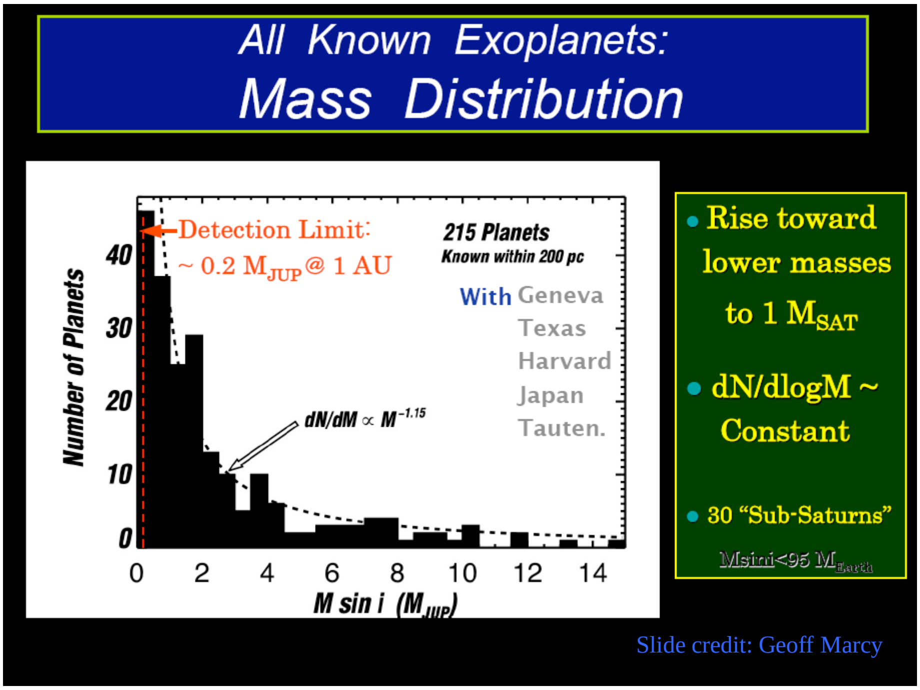
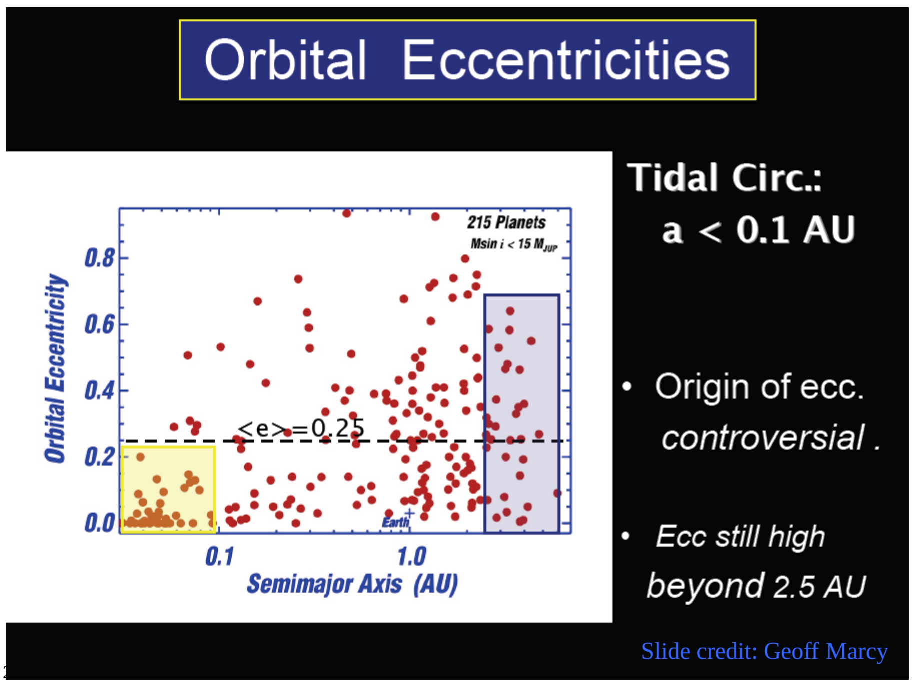
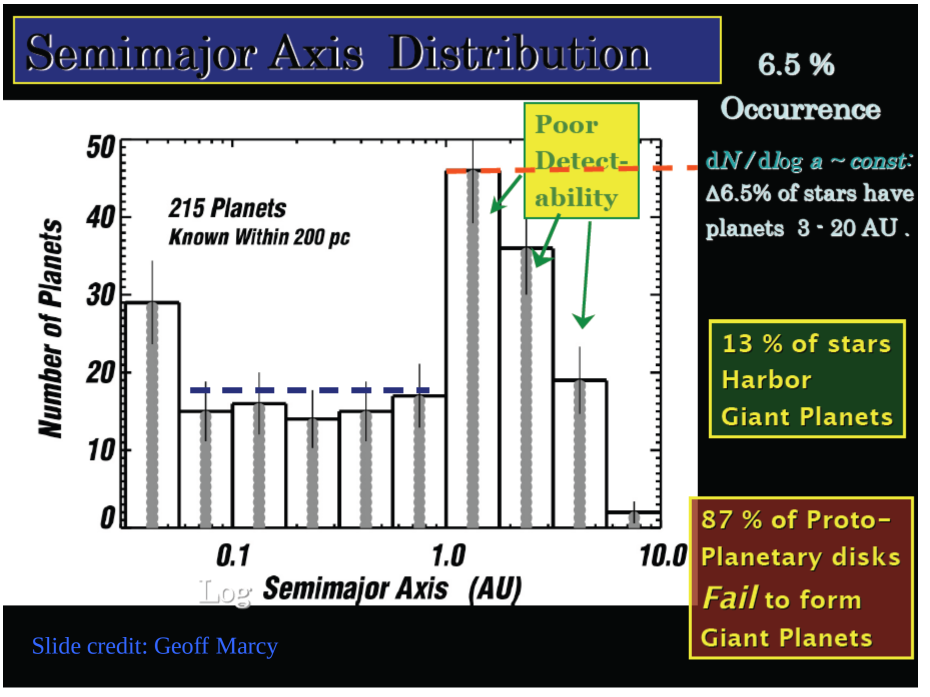

Distribution of orbital sizes for 87 exoplanet systems
One normal Jupiter
Hot Jupiters
Orbital Semimajor Axis (AU)
0
1
2
3
4
5

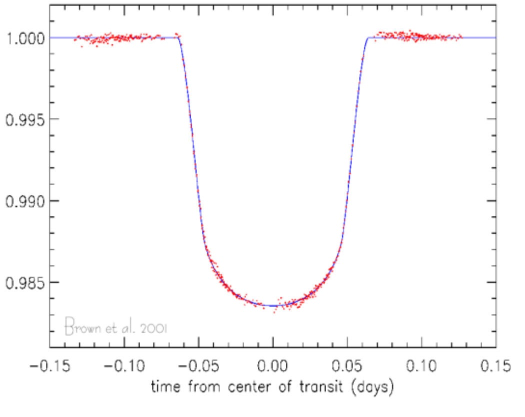

All Known Exoplanets:
Mass Distribution
Detection Limit:
~ 0.2 MJUP @ 1 AU
215 Planets
Known within 200 pc
With Geneva
Texas
Harvard
Japan
Tauten.
dN/dM ∝ M^-1.15
Number of Planets
0
10
20
30
40
0 2 4 6 8 10 12 14
M sin i (MJUP)
Rise toward lower masses to 1 MSAT
dN/dlogM ~ Constant
30 "Sub-Saturns"
Msini<95 MEarth
Slide credit: Geoff Marcy


Orbital Eccentricities
215 Planets
Msin i < 15 MJUP
<e>=0.25
Earth
Orbital Eccentricity
0.0
0.2
0.4
0.6
0.8
0.1
1.0
Semimajor Axis (AU)
Tidal Circ.:
a < 0.1 AU
Origin of ecc. controversial .
Ecc still high beyond 2.5 AU
Slide credit: Geoff Marcy



HD209458

- One of the systems (HD209458), discovered through the Doppler technique, was later found to exhibit transits.
- This must therefore have sin$i$ =1 giving an accurate determination of the mass. (0.69 M_J)
- The size of the planet can be determined from the light curve. (1.347R_J).
- Na I has been detected in the atmosphere of the planet. The star is 2.32×10^{-4} times dimmer at the Na D wavelength (589.3nm) than at an adjacent wavelength.



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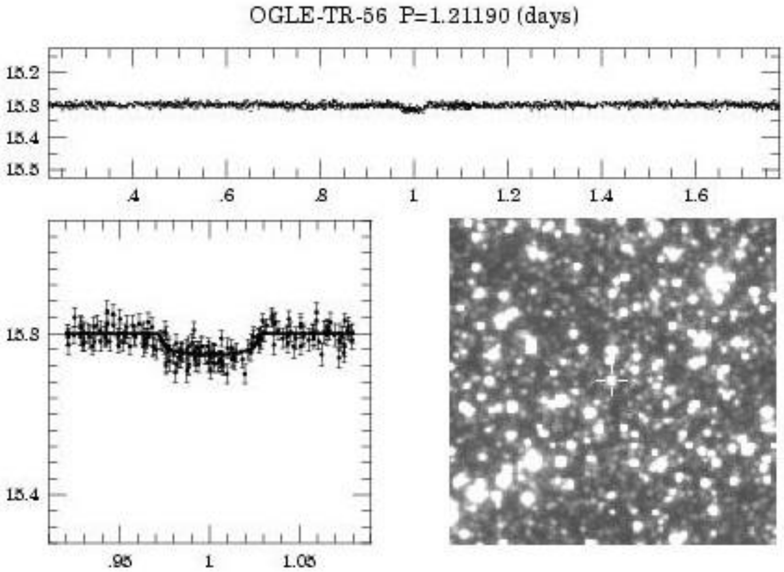
Exoplanet transit candidate (now confirmed)



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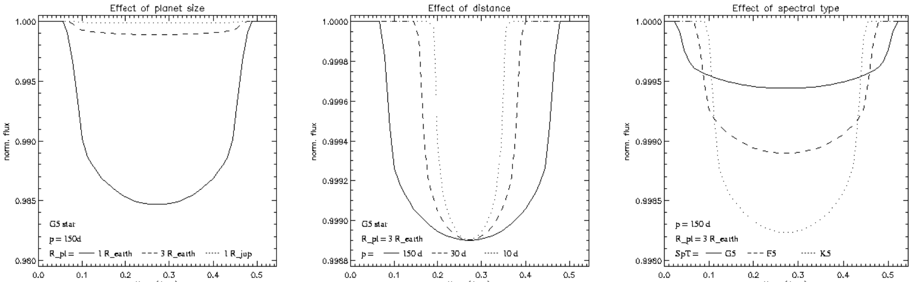
Extra Solar Planets: Indirect Detection: Transits

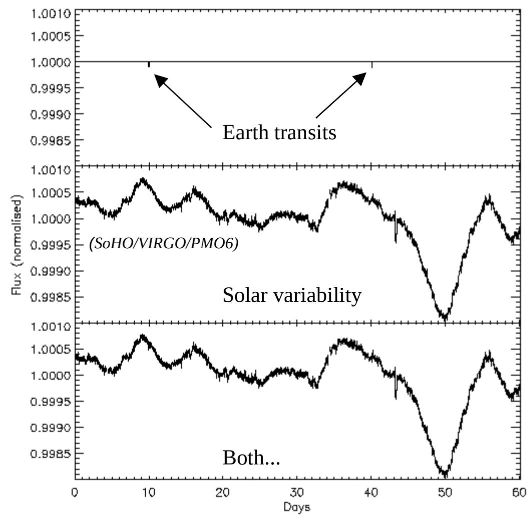


- We can work out the effects of different sizes of planets, the effects of the distance of the planet from the star and the effect of the spectral type on our ability to detect the transit.
- It is clear, however, that we should be able to detect these transits with the right kind of technical approach.
- The other problem is that the probability of a transit occurring is very low because it needs good alignment between the orbital inclination and the line of sight. There is a 1 in 1142 probability of a Jupiter transit being observed but for an earth transit this becomes a probability of 1 in 229.
- A recent paper (Holman & Murray, Science, 25 Feb 2005, p1288) suggests that looking for variations in transit timings will reveal the presence of Earth-size planets in the so-called "habitable zone", even if the smaller planets do not transit.

30 (Graphics from Suzanne Aigrain, IoA)

Extra Solar Planets: Indirect Detection: Transits

- Stellar variability is a serious problem when detecting transits.
- It is due to the stellar revolution and the evolution of structures on the stellar disk.
- We have not detected these small-scale variations from the ground except for young stars: for the Sun they have only been detected by spacecraft such as SOHO.
- The amplitude of these variations is approximately 10^{-3} in the sun.
- An earth transit would only produce a variation of $8x10^{-5}$.
- The spectrum of the variability is complex and has a non-white power spectrum.
- We have no idea how it varies with mass, age, etc of the stars being looked at.
- It will affect all space-based transit searches.



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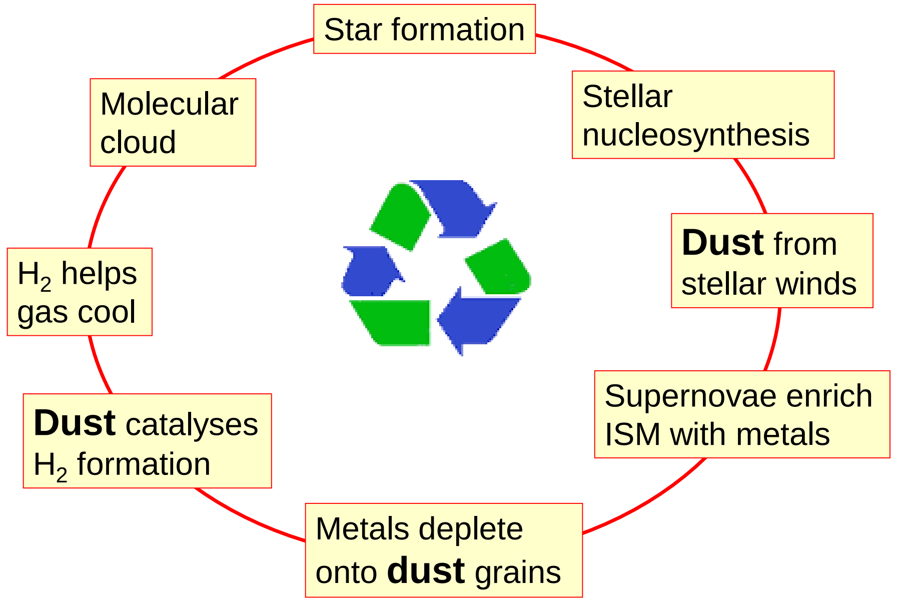
(Graphics from Suzanne Aigrain, Oxford)

Dust: key role in chemical evolution:



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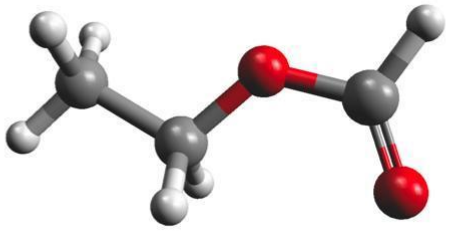
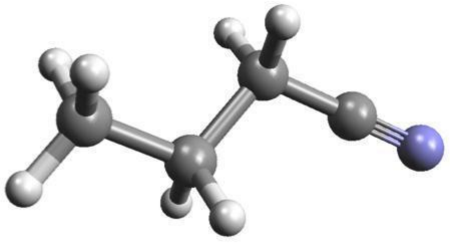
Molecules in Space

- Many new molecules are now known.
- Most are relatively simple, such as CO_2, CH_4, C_2H_5OH.
- More complex ones recently found (2009) such as (Top): Ethyl formate (C_2H_5OCHO). Bottom: n-Propyl cyanide (C_3H_7CN). Colour code of the atomic constituents of both molecules: hydrogen (H): white, carbon (C): grey, oxygen (O): red and nitrogen (N): blue. (Credit: Oliver Baum, University of Cologne)
- The simplest amino acid, glycine (NH_2CH_2COOH), has been successfully detected in the Sag B molecular cloud. These molecules are of similar complexity.





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Extra-solar Planets: Formation

- Our general model of how a planetary system might form is as follows:
- Stars form from **gravitational instabilities** in interstellar clouds of gas and dust grains leading to **collapse** and **fragmentation**.
- Massive stars evolve rapidly creating **new elements** by nucleosynthesis and dispersing them by gaseous **outflows** or **supernovae** explosions.
- Some of the chemically enriched material stays in the gas phase while part of it will condense into solid dust grains such as silicates providing material for subsequent generations of star formation.
- A cloud with some initial rotation will lead to the formation of a flattened system with a high proportion of double and multiple stars arising from the fragmentation process.
- Single star formation then involves three fairly distinct stages that leads naturally to the formation of flattened discs.

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Extra-solar Planets: Formation

- (i) the collapse under self-gravity of an extended cloud of gas (hydrogen and helium atoms and simple molecules of hydrogen, CO, CO_2, N_2, CH_4 and H_2O) and dust grains (typically 10 microns in size each containing a million atoms of C, Si, O, with outer coatings of H_2O or CO_2).
- Much of the material accretes towards the central proto-star but the angular momentum prevents total collapse onto the central object.
- This results in a **rotating disk** with a thickness much smaller than its radius and which will produce a circumstellar disk extending out to about 100 AU, well beyond the orbit of Pluto. This disk probably takes from 10^5 to 10^6 years to form.
- (ii) gas and dust from the disk flows onto the central object by gravity, heating the protostar until **nuclear fusion starts in the centre** on timescales of 10^5 to 10^7 years.
- Material in the disk is replenished by infall from the surrounding molecular cloud.
- (iii) this leads to a centrifugally supported **residual stellar nebula** containing the material that will accumulate to form planets.

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Extra-solar Planets: Formation

- Planetary formation then occurs beginning with **dust grains** settling into a dense layer in the mid-plane of the disk, **sticking together** and forming macroscopic objects with sizes from centimetres to metres.
- This is followed by another stage in which further collisions lead to the **formation of planetesimals**, objects of up to 1 kilometre or so in size where gravitational interactions lead to the concentration of objects in particular orbits.
- Finally gravitational interaction between the planetesimals changes their Keplerian orbits leading to collisions and generally to the **formation of larger objects.**
- The growth of these objects proceeds rapidly once their gravitational attraction becomes large enough (see Hill radius later).
- This planetary accretion process will effectively clear the gap around its orbit in ways that depend on, for example, the (unknown) viscosity of the general planetary disk.
- In our solar system, planetesimals that grew to modest size without joining larger objects, as well as collisional debris are represented by meteorites (made essentially out of rock, and up to a few hundred metres in size) and comets (essentially dirty snowballs of frozen water and carbon dioxide and dust grains, up to a few kilometres in size).

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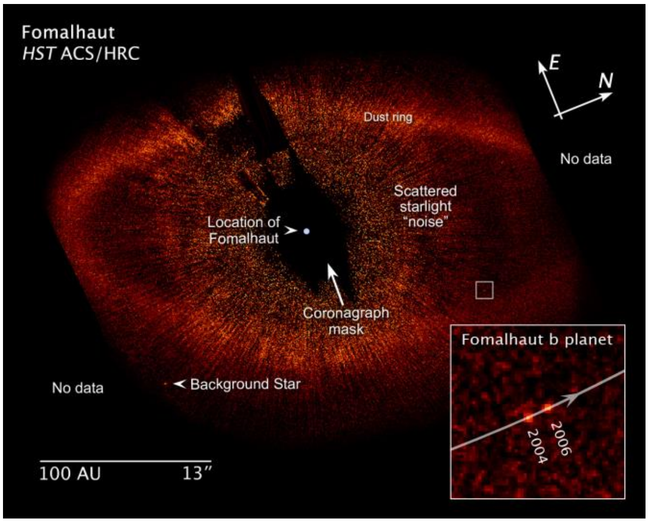
Extra-solar Planets: Formation



- HST coronagraphic image of Fomalhaut at 600 nm, showing the location of Fomalhaut b (white square) 12.7 arc sec radius from the star and just within the inner boundary of the dust belt.
- All the other apparent objects in the field are either background stars and galaxies or false positives.
- The fainter lower half of the dust belt lies behind the sky plane. The Hubble data represent the first visible-light image of a planet circling another star. (Kallas et al.,Science, 28 Nov 2008)

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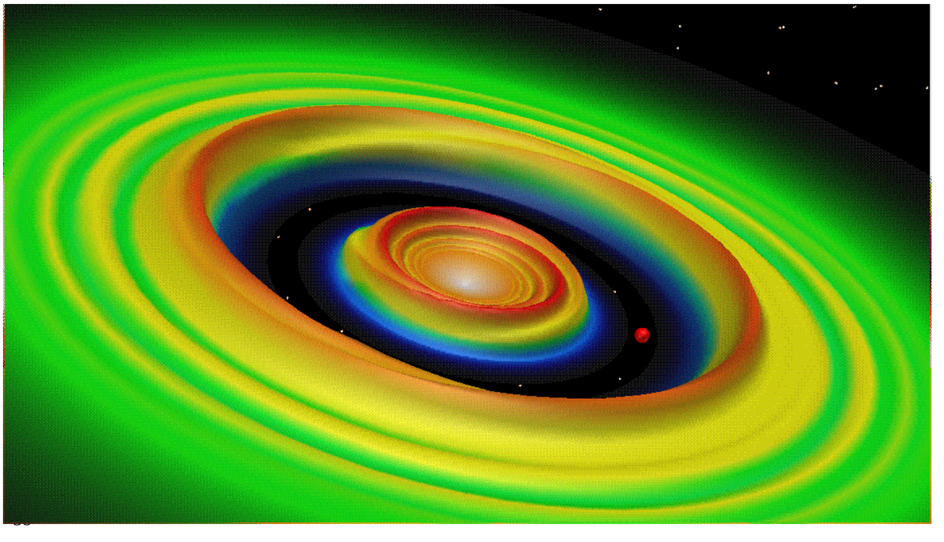
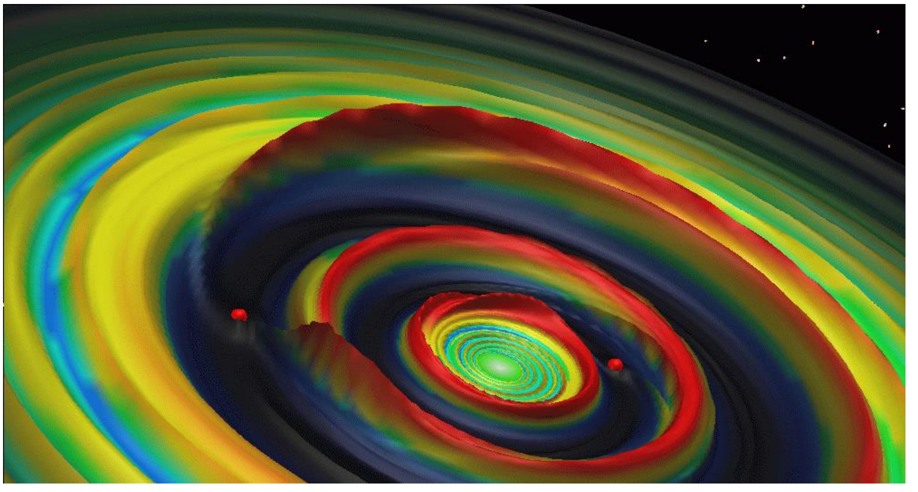
Once a planet grows large enough it makes a gap in the gas disk



2 Jovian planets – after 100 orbits



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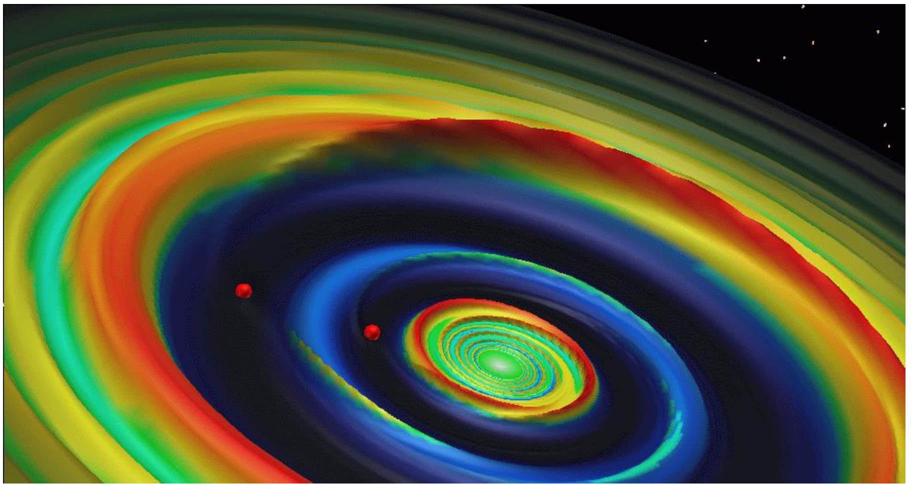
2 Jovian planets – after ~300 orbits



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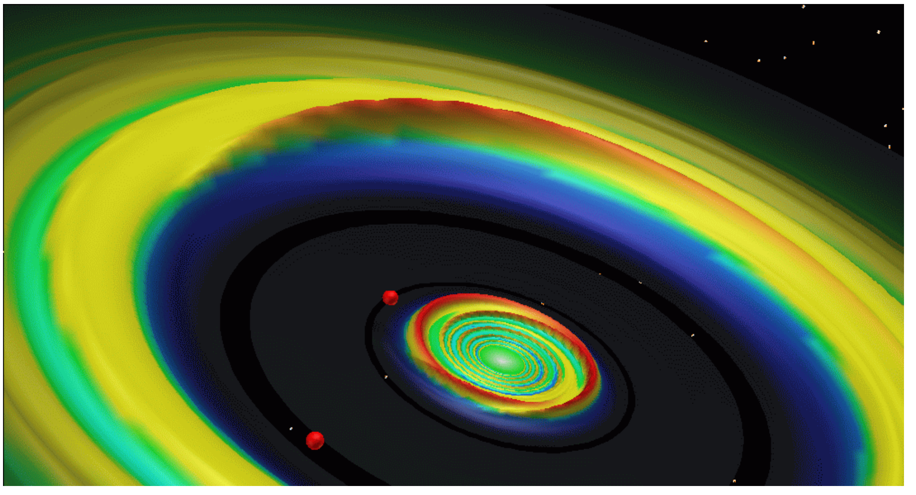
2 Jovian planets – after 1000 orbits



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Formation of “Hot Jupiters”

- Cannot have been formed at their present proximity to the star because:
  - too hot for grain condensation.
  - not enough solids to build core in < 3Myr.
  - not enough gas to build the outer envelope.
- Current theory is that the planet forms further out and migrates inwards due to differential torque from the gaseous disk.
- Problems: Why don’t they all fall in to the star? Why is Jupiter so far out? Why is the eccentricity distribution random?

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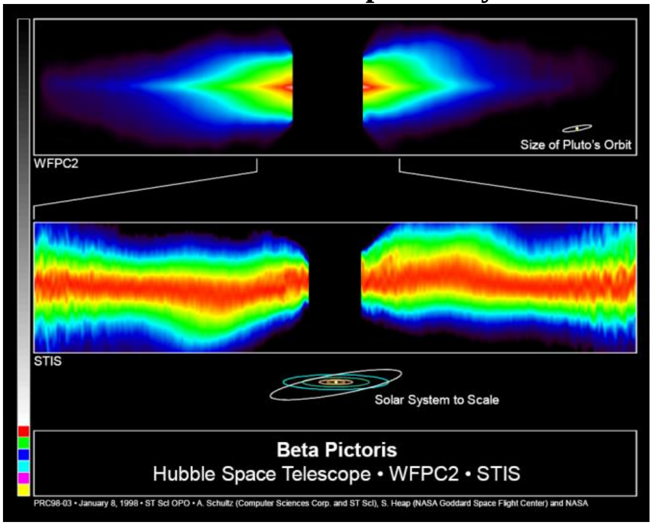
Extra Solar Planets: Observation of Proto-planetary Discs

- Numerical simulations of planet formation produce a thin disk of gas and dust that leads to a planetary system much like our own.
- Is there any evidence, however for the existence of possible sites of planet formation?
- Hubble images of the star β Pictoris reveal an extensive disk surrounding the central star.
- The spectrum of the system shows both star and disk contributions.



- The disk is heated by the star, and the temperature of the disk decreases with increasing radius.
- We can model the disk spectrum as a series of rings each of area = $2\pi R\Delta R$, radiating as a black body.
- Some discs show a lack of a high-temperature contribution from material at 10-30 AU which may be an indication of a gap in the disk in which a planet might form.

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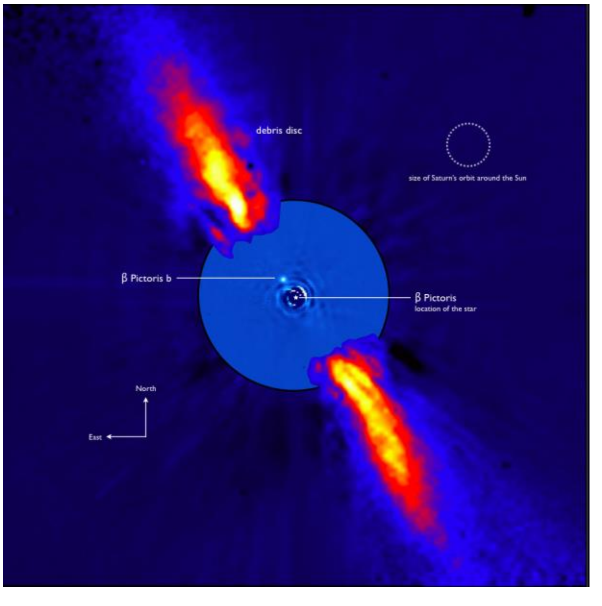
Extra Solar Planets: Observation of Proto-planetary Discs

- This is an image taken of β Pictoris in the near infrared at 1.25 microns taken on a 3.6 metre telescope in Chile with a coronographic imager (an instrument that blocks out the central bright star with minimum scatter). The image is 13 x 13 arc seconds (~220 AU) and the spatial resolution is 0.12 arc seconds.
- The disk is visible to within about 24 AU of the central star.
- The image shows a pronounced warp of the disk which has been interpreted as indicating a planet at a distance of ~ 20 AU from the central star in an orbit inclined at about 3° to the plane of the disk.



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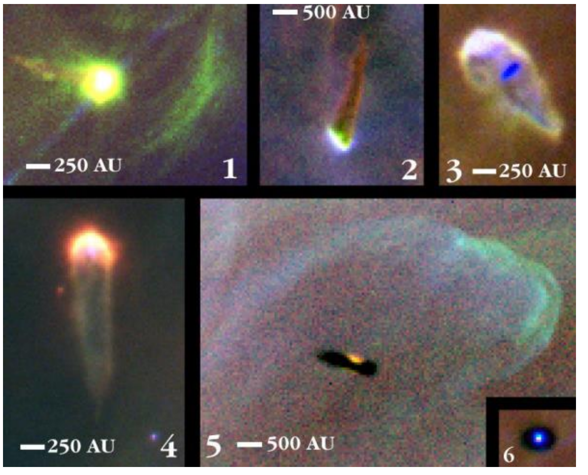
Extra Solar Planets: Observation of Proto-planetary Discs



- What evidence do we have for the existence of sites at which planets might be formed?
- The star β Pictoris has M = 3.9 a spectral type A5V (much hotter than the Sun) and is at a distance of 17 parsecs. In 1983 the IRAS satellite discovered it was very bright at far infrared wavelengths indicating it had a large dust/gas disk.
- There are now a number of such systems known.
- This is a montage of several protoplanetary systems detected with HST in the Orion nebula.
- We see dense molecular cores in star forming regions such as the Orion nebula. Their masses are about one solar mass and are about 0.1 parsecs across. Radio observations of the temperature and velocity of the molecules in these clouds allow us to work out their angular momentum.
- The collapse time $t_{ff} = (3/(2\pi G\rho))^{½} \sim 6x10^5$ years to give a rotating disk.

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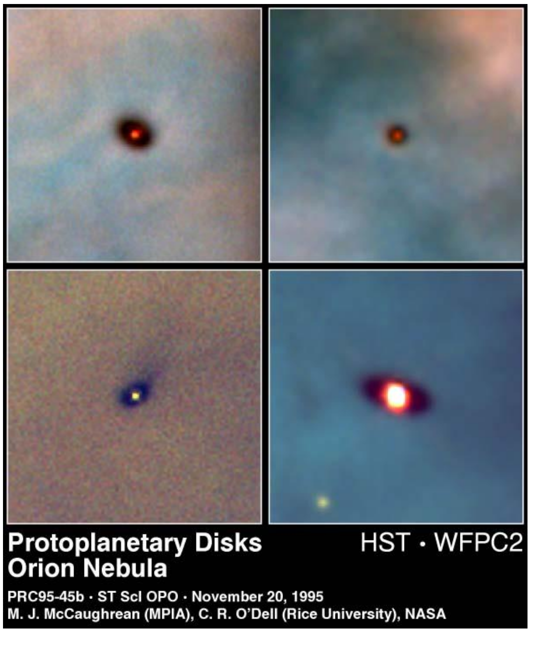
Extra Solar Planets: Observation of Proto-planetary Discs

- These are examples of protoplanetary discs in the Orion nebula.
- Each of these square images is approximately 30 times the size of the solar system.
- The images are made as composite images from three separate colours from three different emission lines and so they show the existence of relatively hot gas in the regions of these objects.



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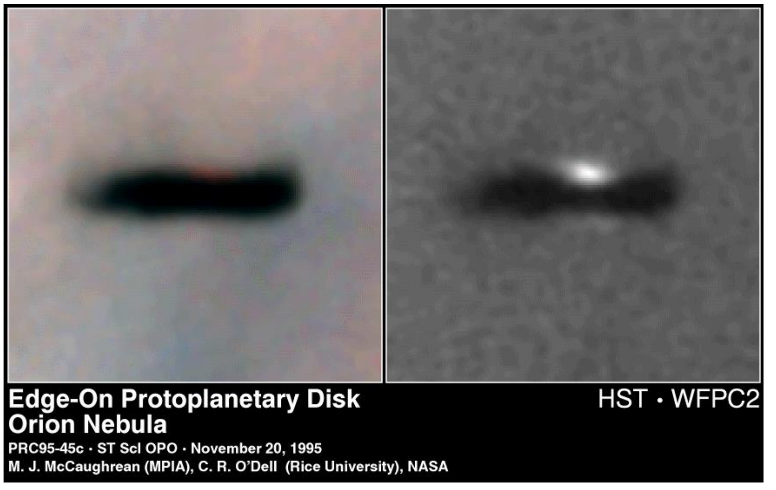
Extra Solar Planets: Observation of Proto-planetary Discs



- These images show an edge-on protoplanetary disk.
- The left hand image is another three-colour composite of the disk while the picture on the right is taken in the infrared and shows the central star beginning to shine through the dust in the disk.

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Forces on dust grains

- We will consider 3 forces that act on dust grains near a star.

1. The radiation pressure force due to momentum transfer from photons.
2. The gravitational force.
3. The photophoresis force due to gas particles which hit the dust grain and recoil differentially due to a temperature gradient across the grain (asymmetric Brownian motion).

- Momentum flux (momentum per unit area per unit time) = pressure
- For photons the radiation pressure
  P_{rad} = (energy flux)/c
- But the energy flux at a distance *a* from a star with luminosity L is $L/(4\pi a^2)$
  So $P_{rad} = L/(4\pi a^2 c)$
- and the force on a dust grain of radius r is
  $$F_{rad} = \pi r^2 P_{rad} = Lr^2/(4a^2 c)$$

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The gravitational and photophoresis forces on a dust grain

- This is simply $F_{grav} = GM_* m_{grain}/a^2$, where M_* is the mass of the star and m_{grain} is the mass of a dust grain. Putting $m_{grain} = (4/3)\pi r^3 \rho_{grain}$ we get $F_{grav} = 4\pi r^3 GM_* \rho_{grain}/3a^2$

- Dust grains will have a hot side and cold side due to incident star light. The energy flux through the dust grain will be the thermal conductivity of the grain times the temperature gradient across the grain, i.e. $K\Delta T/r$

- If the grain is in equilibrium this will be equal to the energy flux *I* of the star light hitting the grain.
- So we can write $I = K\Delta T/r$ [1]

- Suppose the dust grain is surrounded by a gas so it is continuously bombarded by particles of the gas.
- Also suppose that the mean temperature of the grain is the same as the temperature of the gas.

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The gravitational and photophoresis forces on a dust grain

- The flux of particles hitting the grain (number per unit area per unit time) = nv, where n is the number density of the particles and v is their characteristic velocity for the temperature T.

- On the hot side of the grain the momentum of a recoiling particle is mv_{hot} and on the other side it is mv_{cold} where v_{hot} is the characteristic velocity for the temperature $T+\Delta T/2$, v_{cold} is the characteristic velocity for the temperature $T-\Delta T/2$ and m is the mass of a gas particle.

- The momentum imbalance for one pair of particles is therefore $\alpha \sim mv(\Delta T/T)$
- The photophoresis force on a grain is the total momentum imbalance per sec so we can write F_{ph} = [gas particle flux] × [grain area] × α

- Hence $F_{ph} = nv \times \pi r^2 \times mv(\Delta T/T)$

- But ΔT is given by [1] and the gas pressure $P = \rho v^2 = nmv^2$

- So $F_{ph} = P\pi I r^3/(TK)$

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Forces on dust grains

- The radiation pressure force $\propto r^2$ and pushes the grains outwards.
- The gravitational force $\propto r^3$ and pushes the grains inwards.
- The photophoresis force $\propto r^3$ and pushes the grains outwards.
- If we set $F_{rad} = F_{grav}$ then we find there is a critical grain size $= 3L/(16\pi cGM_* \rho_{grain})$ above which gravity wins. Note this is independent of the distance from the star.
- Grains in the interstellar medium are about 0.1 microns across. For a grain density of 10^3 kg/m^2 the critical grain size in the solar system is ~ 0.6 microns. Grains maybe "fluffy", i.e. lower density, making critical size larger.
- Need to understand how ISM grains can grow without being blown away by radiation (or photophoresis).
- Grains in proto-planetary disks are thought to be up to 50 microns or more in size.

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Presence of planets correlates with metalicity

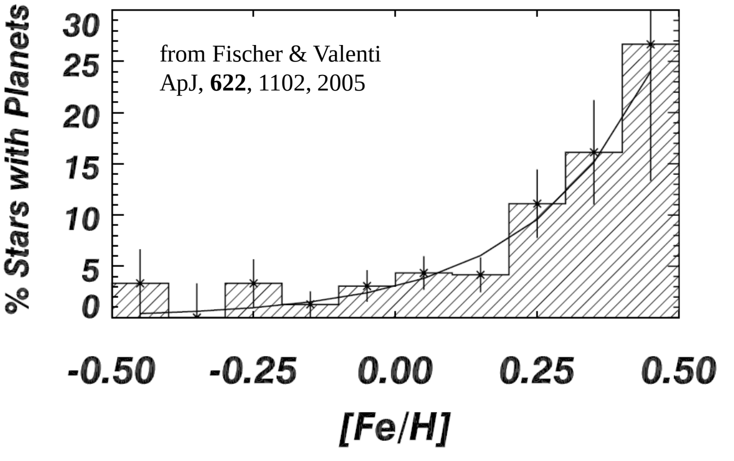

FIG. 5.—Same results as Fig. 4, but divided into 0.1 dex metallicity bins. The increasing trend in the fraction of stars with planets as a function of metallicity is well fitted with a power law, yielding the probability that an FGK-type star has a gas giant planet: $\mathcal{P}(\text{planet}) = 0.03[(N_{\text{Fe}}/N_{\text{H}})/(N_{\text{Fe}}/N_{\text{H}})_{\odot}]^{2.0}$.

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The Hill Radius

- This is a measure of the size of the sphere of gravitational influence of a low mass object (e.g. a planet) which is in orbit around another object of much larger mass (e.g. a star).
- Within this distance a third, very small object, can have a stable orbit.
- Outside this distance a very small object will eventually be perturbed and captured by the much larger mass object.
- For example, in the solar system, all the moons of the planets lie within the Hill radius for their planet.
- When planetary systems are forming, planetesimals can capture material that orbits within their Hill radius.
- Let us derive the Hill radius for a planet orbiting a star.
- First equate the orbital velocity of the satellite to the orbital velocity of the planet around the star $\Omega_{satellite} = \Omega_{planet}$
- So Kepler's 3rd law gives us $$\sqrt{\frac{GM_{planet}}{R_H^3}} = \sqrt{\frac{GM_\star}{a^3}}$$
- Where R_H is the Hill radius and a is the semi-major axis of the planet's orbit around the star.
- Solving for R_H we get $$R_H = a\left(\frac{M_{planet}}{M_\star}\right)^{1/3}$$

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The Hill Radius - examples

- For the space shuttle (M~100 tonnes) in low earth orbit, the Hill radius is only 1.2 metres so stuff (astronauts, cigarette butts, etc.) won't orbit it.
- The Hill radius for Jupiter is 53 million km.
- The Hill radius for Neptune is 116 million km (largest in solar system because it is a long way from the Sun).
- The Hill radius for the Earth is 1.5 million km.
- For a 1kg "planetesimal" at 1 AU from a solar mass star the Hill radius is 12m. So as long as the planetesimal has a radius less than 12m (quite likely) it has already grown big enough to have a gravitational sphere of influence.

- Exercise: what size planetesimal has a radius equal to its Hill radius at 1AU from a solar mass star with a density of 1000kg/m^2?

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Future Ground-based observations

- Direct detection with 5 – 10m telescopes in the NIR using extreme adaptive optics plus a coronograph plus multiwave-band imaging (Project 1640 and Gemini Planet Imager).
- Direct detection using similar methods but with future extremely large (>30m) telescopes (ELTs)?
- Follow up spectroscopy with ELTs of planets discovered from space.
- Transit searches.
- Ground-based interferometers (VLTI, Keck).
- ALMA after 2010 (huge mm array, very accurate astrometry)

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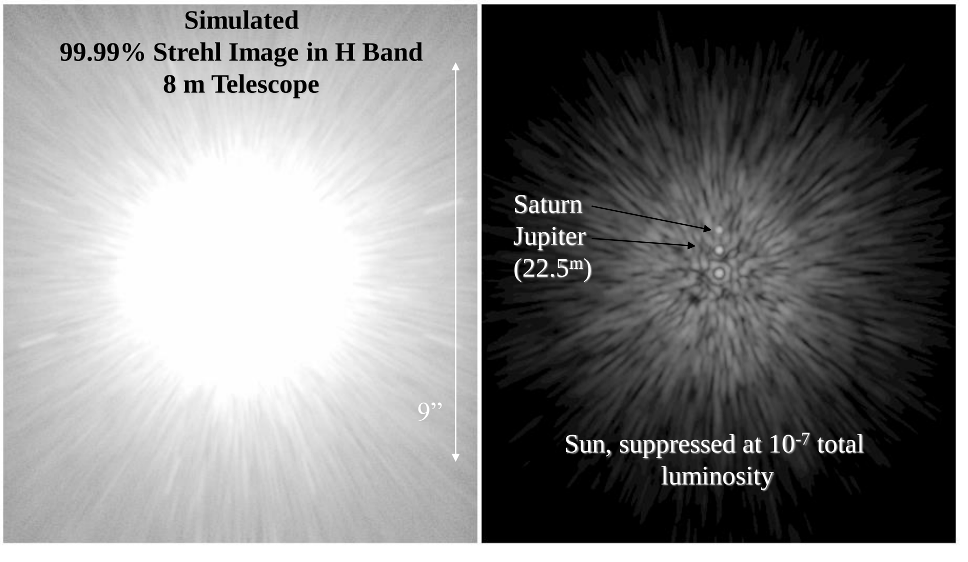
What is theoretically possible from the ground with an 8m telescope Solar System Analog at 10 pc



Space-based exoplanet observations

- HST astrometry program, now →
- SPITZER, 25th Aug 2003→, loosing sensitivity as cryogen exhausted, for studies of planetary discs
- MOST 2003 →, 15cm, photom. of a few bright stars
- COROT. Dec 27th 2006 →, 27cm, photometry of ~30 stars
- Kepler. Feb 2009 → 0.95m, far infrared imaging, transits, terrestrial planets.
- GAIA (2012) → astrometry, very high positional accuracy
- JWST 2021? →, 6.5m, coronograph, mid-IR

- SIM 2015 →, optical, Space Interferometer Mission, 10m baseline, lensing , 4μas.
- Darwin, ESA, 2020? →
- Terrestrial Planet Finder, NASA, 2020? → like DARWIN

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Recently Launched Missions

MOST

- Will look for reflected light from known giant planets orbiting nearby bright stars.

SPITZER

- Has studied hundreds of nearby stars and look for circumstellar disks.
- Measured spatial structure and chemical composition of these disks.
- Recently measured atmospheric composition of transiting exoplanets (less water found than expected).

- Cryogens are now exhausted, so IR cameras have warmed up and are now very much less sensitive.

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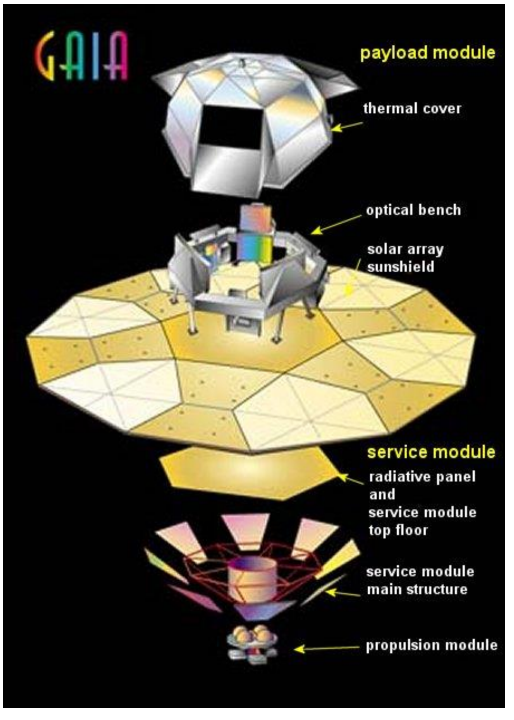


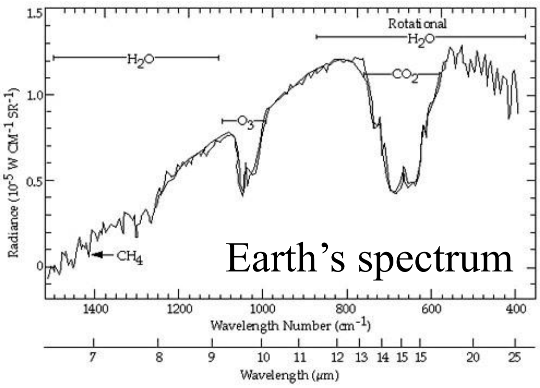
GAIA

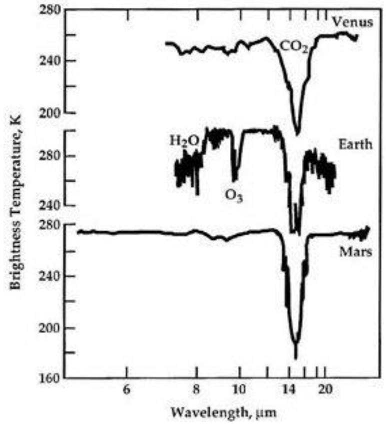
- Astrometry, photometry and spectroscopy of 10^9 stars!
- 2 astrometric telescopes
- 1 spectroscopic telescope
- Each star observed ~100 times in 5 year mission
- 200 times more precise than Hipparcos (10μas)
- 250 CCDs (1.5 billion pixels)!
- Main goal is galactic structure.
- However, via astrometry, expects to detect **<u>all</u>** existing Jupiter-mass planets within 50pc of the Sun! (orbital periods between 1.5 and 9 years). No sin*i* degeneracy.
- Expects to find 10,000 to 50,000 Jupiter-mass planets in total survey out to ~200pc.

DARWIN CONCEPT

- ESA, launch 2020? Status very uncertain.
- L2 orbit, 8 craft in formation
- 6 × 1.5m telescopes (or perhaps 3 × 3m telescopes)
- a central hub
- a communications satellite
- spectroscopy to look for signatures of life
- nulling interferometer with a 30m baseline (see earlier).

Detecting Ozone – a signature of life





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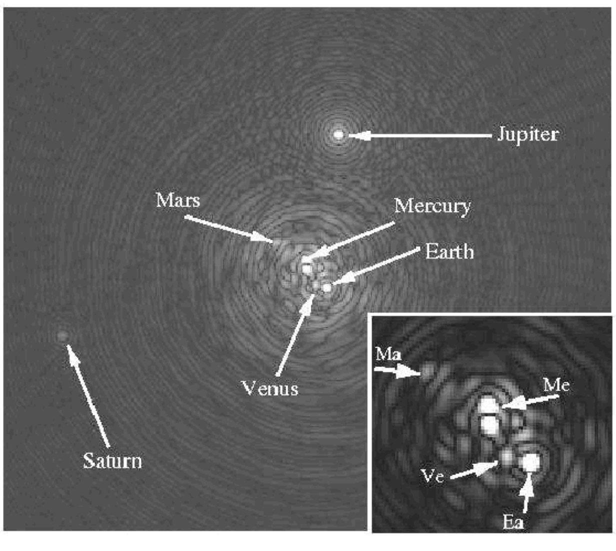

Fig. 8. Simulated image of the solar system's planets at a distance of 10 *pc*. The values adopted for angular separations and fluxes are given in Table 3. No photon noise has been included. The image of the Sun was numerically substracted.

What DARWIN or TPF might see

Image is at 10µm. Exposure time is 10 hours. This simulation assumes 6, 3m telescopes on a 60m baseline.