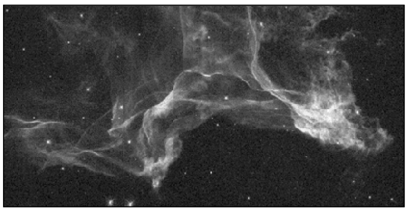
A planet-building universe

production

dissemination

- The top ten elements:

		production	dissemination
H	100.000	big bang	big bang
He	9.700	big bang	big bang
O	0.085	He fusion	supernovae
C	0.036	He fusion	planetary nebulae
Ne	0.012	C fusion	supernovae
N	0.011	H fusion	planetary nebulae
Mg	0.004	Ne, C fusion	supernovae
Si	0.004	O fusion	supernovae
Fe	0.003	supernovae	supernovae
S	0.001	O fusion	supernovae



Note that the most common elements in your body all occur in the top ten, formed by a variety of mechanisms (most obvious absentees are calcium and phosphorus)

A planet-building universe

- Massive stars produce heavy elements
  - and disseminate them into interstellar medium via planetary nebulae and supernovae
- Heavy elements in cool gas tend to clump together to form small dust grains
  - reason for opacity of gas clouds in Milky Way
- Theory and observation (cratering record) suggest planets of solar system formed by accretion
  - dust grains collide and stick to form successively larger bodies
  - probably fairly easy process if stars form from dust-rich material

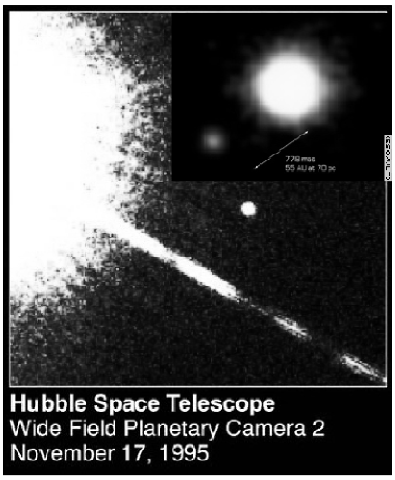
Detection of extrasolar planets

- Over 850 planets have now been observed around other stars
  - how are they detected?
  - what do they look like?
  - what do they tell us?

- How do planets form?
- Are planets common?
- Is our system typical?
- Are Earth-like planets common?

First, find your planet...

- Can we observe planets directly?
  - hardly ever with current technology (<u>but...</u>)
    - planets too faint compared with their star
    - this brown dwarf is just visible - and its star is a red dwarf
    - this suspected planet is orbiting a brown dwarf
  - planets shine by reflected light
    - the brighter the planet, the closer it must be to its star

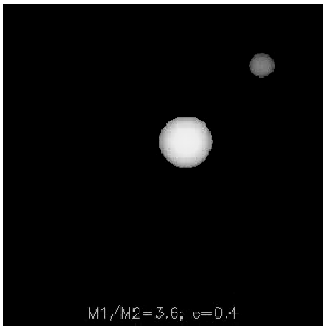


Finding invisible planets

- Gravitational force is mutual: planet pulls on star as much as star on planet
  - star must move around system centre of mass
    - it changes position on the sky
    - it moves along line of sight
  - problem: star is much more massive than planet
    - so won't move much, or very quickly
- Example: Sun and Jupiter
  - Sun weighs 1000x Jupiter
    - Radius of Jupiter's orbit around centre of mass: 5.2 AU
    - Radius of Sun's orbit: 0.0052 AU
    - Radius of Sun: 0.0047 AU
    - ➔ From nearest star, Sun's motion like 1p piece seen from 600 km away!
    - Orbital velocity of Jupiter: 13 km/s
    - Orbital velocity of Sun: 13 m/s
    - ➔ wavelength shift of 1 in 20 million!

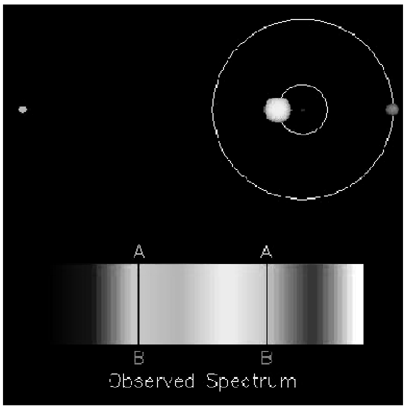
Method 1: astrometry

- Look for star moving across sky
  - used to detect presence of Sirius B (white dwarf)
  - need nearby star
    - to detect motion
  - need **massive** planet **far** from star
    - maximise size of star's orbit
    - long period: need long series of observations
- Only one or two detections



Method 2: Doppler shift

- Look for periodic shift in star's spectrum
  - does not depend on distance of star
  - need **massive** planet **near** star
    - the closer the planet, the faster the orbital speed (of both planet and star)
  - need very good spectrum
    - measure Doppler shifts of <1 in 1000000
- Most confirmed detections use this method
  - and it is used to confirm transit candidates



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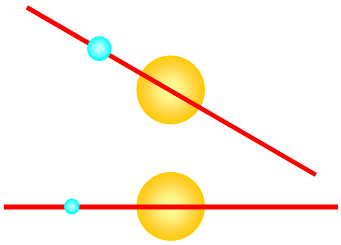
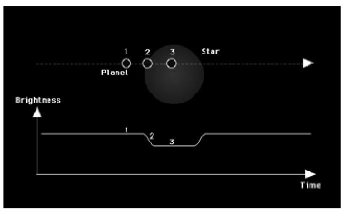
Problems….

- Doppler shift only detects velocity along line of sight
  - can't distinguish massive planet (or brown dwarf!) in tilted orbit from less massive planet in edge-on orbit
  - usually nothing to be done about this
    - might see planet move across face of star (transit)
    - can try astrometry





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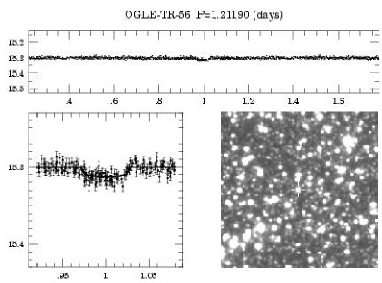
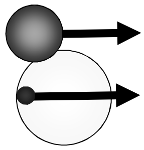
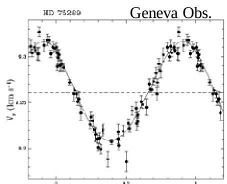
Method 3: transit

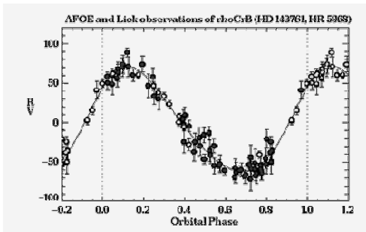
- Observe small drop in light from star as planet passes across it
  - amount of drop indicates size (not mass) of planet
  - interval between transits gives period
  - needs confirmation by radial velocity measurements
    - otherwise could be grazing eclipse by stellar companion
- Increasingly important technique

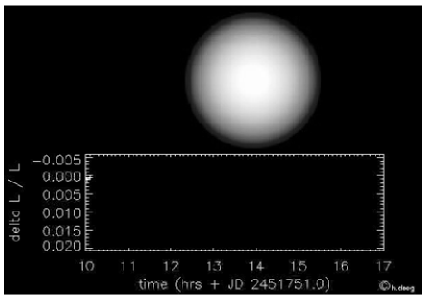




Some data….



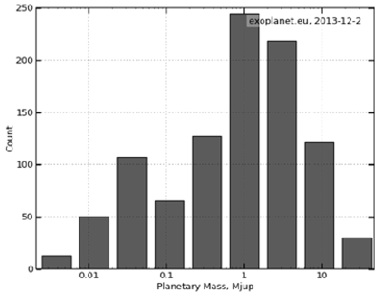




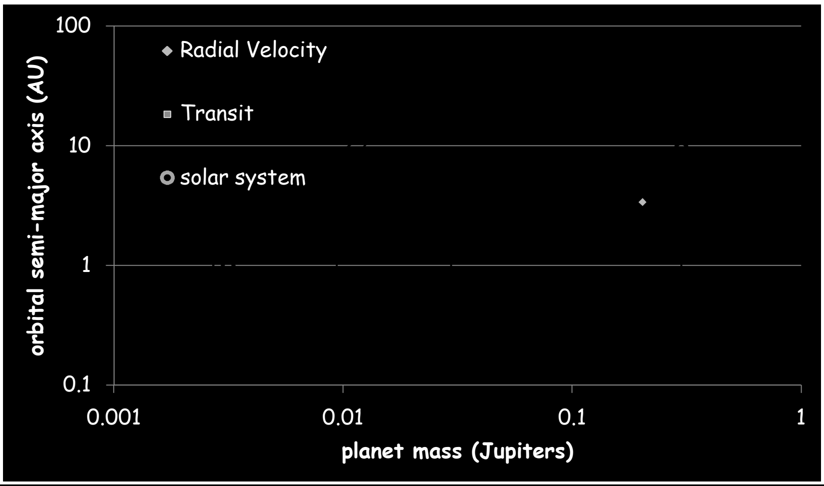
Transit observations show that this planet has a radius about 1.5x Jupiter and a mass of 0.69x Jupiter.

Known extrasolar planets

- Massive (2 Earth - 30 Jupiter) and close to star (many <1 AU)
  - ***this is a selection effect*** (caused by detection method)
    - but does show that such planets exist!
  - most masses are minimum values
    - but 424 planets transit
    - 25 found by gravitational lensing
    - 44 directly imaged
  - some presumably brown dwarfs (>13 M_J)
    - but surely not all (random orientation)

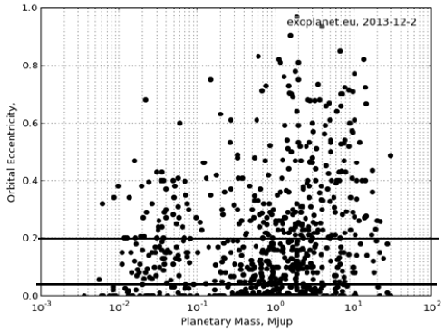


Known extrasolar planets



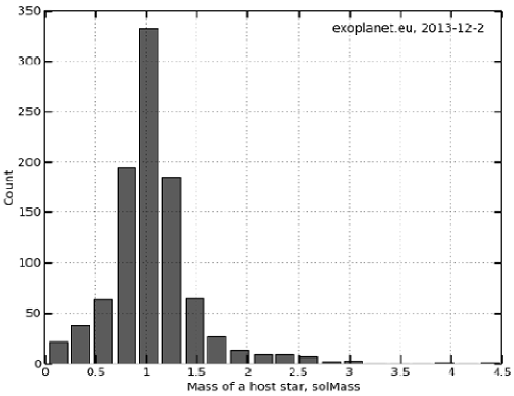
Orbits

- Solar system planets in near-circular orbits
- Binary stars (and brown dwarfs?) often in eccentric orbits
- Many of these objects are in eccentric orbits
  - but no clear correlation with mass
  - no evidence for two distinct types of body



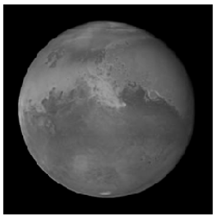
Parent stars

- High in heavy elements (usually >Sun)
  - reasonable: planets form from dust
- Roughly solar type (F7 - K2)
  - probably some selection bias: there are a few low mass stars
  - ultra-accurate spectroscopy difficult in cool stars because of complex spectra

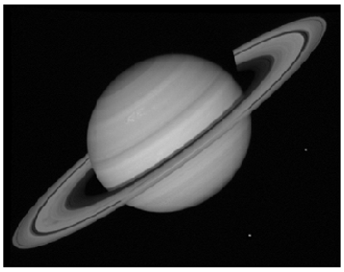


What are these planets?

- Solar system has small rocky planets close to star, large gas giants further away
  - no experience of large planets close to star
  - generally assume these are gas giants, but direct evidence only for transiting planets


Mars by HST

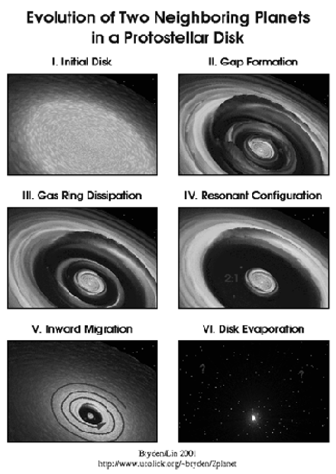
Voyager

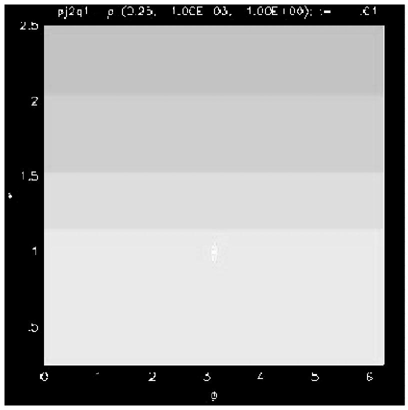


How are they formed?

- Our theory for solar system:
  - stellar wind from young Sun blows volatiles outwards
  - "snowstorm" at 5 AU where water-ice solidifies
  - fast accretion of large icy planet (~10 M_{Earth}) which then collects H/He atmosphere
    - gas giants Jupiter, Saturn just outside "snow line"
    - small rocky planets inside
    - slowly accreting icy planets in outer system (Uranus, Neptune)
- Extrasolar "hot Jupiters":
  - do they form in situ?
    - looks impossible: too hot for ices, too little material for rock
  - do they form outside snow line and migrate?
    - planet forms in gas/dust disc around star
    - drag from remaining gas/dust causes it to spiral inwards
    - why does it stop?
  - why didn't Jupiter do this?
    - current theory—it did, but moved back out owing to interaction with Saturn
    - see PHY106

Formation of “hot Jupiters”





Movie by Willy Kley

What have we learned?

- Using Doppler shift measurements we have detected planets round ~800 nearby stars
  - relatively massive planets close to stars, often in eccentric orbits
    - not what was expected
    - may arise when Jupiter-like planets migrate inwards after formation
  - mainly single planets
    - 174 multi-planet systems containing up to 7 detected planets
    - solar system has only 1-2 detectable giant planets
- What does this imply?
  - does not imply that such systems are typical
    - detection method is biased
  - does imply that they are possible!
  - does not imply that systems like ours are uncommon
    - Jupiter is barely detectable
  - but does not provide evidence that they are common!
- No evidence yet for “other Earths”

...speculation next lecture!