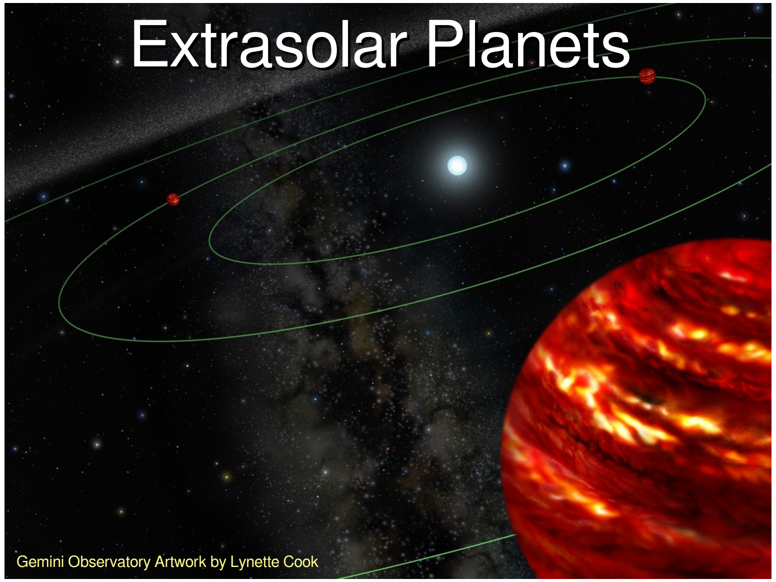



Extra-solar Planet Trivia

1) When was the first extra-solar planet found around a Sun-like star?
   a) 1981   b) 1995   c) 2000   d) last month

2) How many extra-solar planets do we know today?
   a) ~30   b) ~300   c) ~ 3000   d) ~30000

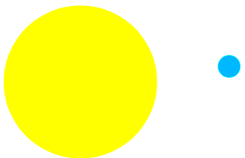
3) What percentage of neighbouring stars are **known** to have planets?
   a) 0.1%   b) 1%   c) 10%   d) 100%

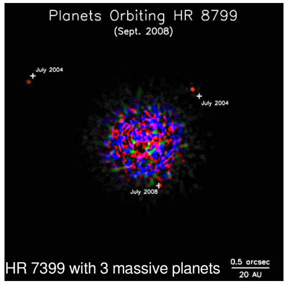
4) What is the lightest among these planets?
   a) like Earth   b) like Uranus (14 $M_\oplus$)   c) like Jupiter (300 $M_\oplus$)

5) By 2020, how many do you think would have been found?

6) What do you think is the most significant reason that we bother?

Detection:
1. Direct imaging – first successes!



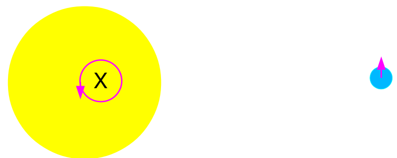



*Contrast (reflected light):* $\frac{A\pi R_p^2}{4\pi a^2} \simeq 10^{-8}\left(\frac{A}{0.2}\right)\left(\frac{R_p}{R_J}\right)^2\left(\frac{a}{1\,AU}\right)^{-2}$

*Contrast (thermal radiation):* $\frac{\pi R_p^2}{\pi R_s^2}\left(\frac{T_p}{T_s}\right)^4 \simeq 10^{-6}\left(\frac{R_p}{R_J}\right)^2\left(\frac{T_p}{600\,K}\right)^4$

*Angular separation:* $0.1\,arcsec\left(\frac{a}{1\,AU}\right)$ $@10\,pc$

Detection:
2. Stellar motion
 – working very well

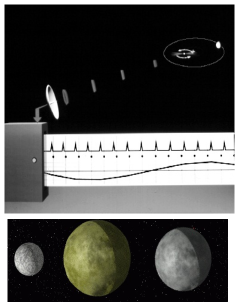


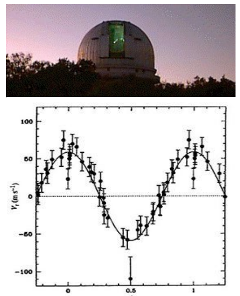

sin i ambiguity

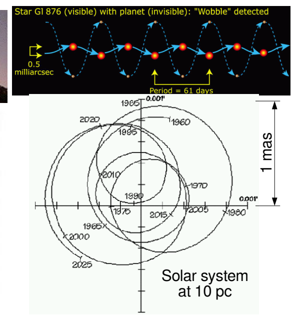
*A) Pulsar timing:* $\Delta t \sim 0.5\,s\left(\frac{a}{1\,AU}\right)\left(\frac{M_p}{1\,M_J}\right)$

*B) Radial velocity:* $\Delta v \sim 30\,m\,s^{-1}\left(\frac{a}{1\,AU}\right)^{-1/2}\left(\frac{M_p}{1\,M_J}\right)$

*C) Astrometry:* $\Delta\theta \sim 0.1\,mas\left(\frac{a}{1\,AU}\right)\left(\frac{M_p}{1\,M_J}\right)\left(\frac{d}{10\,pc}\right)^{-1}$



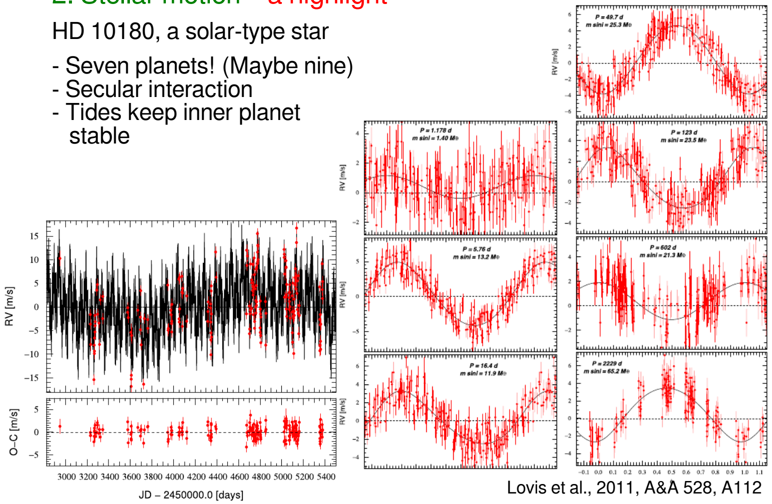




## Detection:
## 2. Stellar motion – a highlight

HD 10180, a solar-type star

- Seven planets! (Maybe nine)
- Secular interaction
- Tides keep inner planet stable




Lovis et al., 2011, A&A 528, A112

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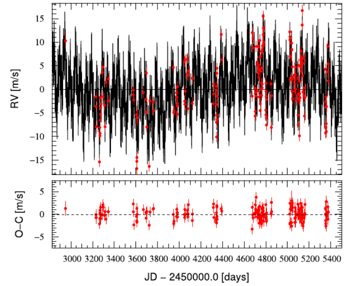
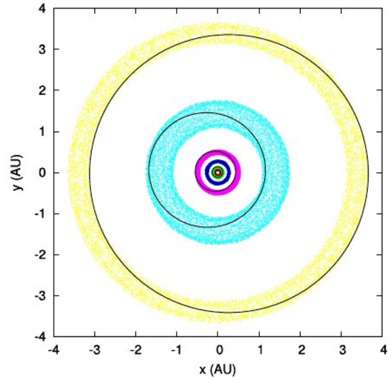
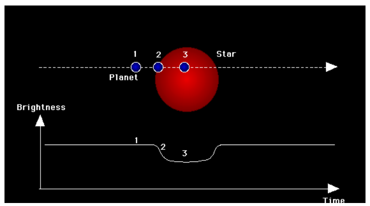


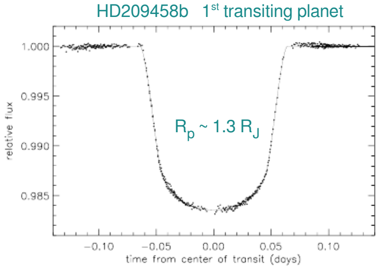




Lovis et al., 2011, A&A 528, A112

## Detection:
## 3. Transits – working very well




HD209458b 1st transiting planet

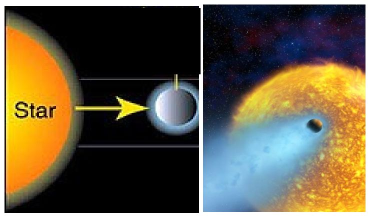



*Eclipse depth:* $\frac{\pi R_p^2}{\pi R_s^2} \sim 0.01$

*Probability:* $\sim \frac{R_s}{a} \sim 0.05\left(\frac{0.1\ AU}{a}\right)$

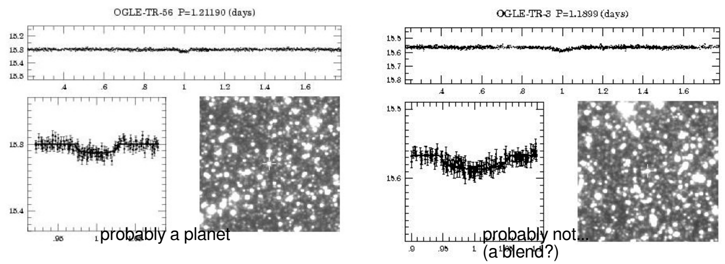
Large scale transit surveys
1) ~1% F/G/K stars have close-in planets
2) ~4% chance of seeing eclipse (a= 0.1 AU)
3) Observe ~$10^4$ stars for a few planets
4) OGLE, HAT... [ground], Corot, Kepler... [space]

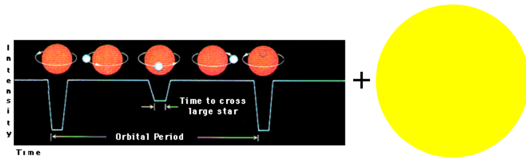
Its atmosphere has sodium, is evaporating, and has strong winds




## Detection:
## 3. Transits (cont'd)

The Optical Gravitational Lensing Experiment (OGLE)

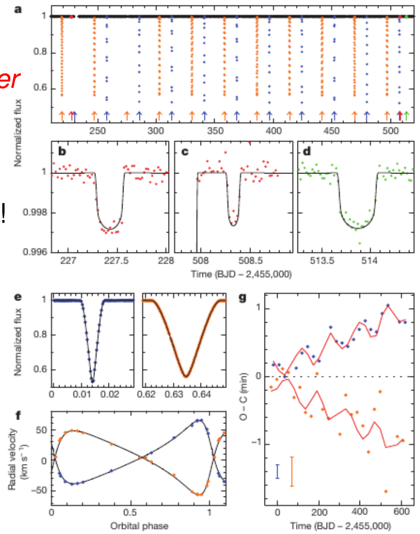


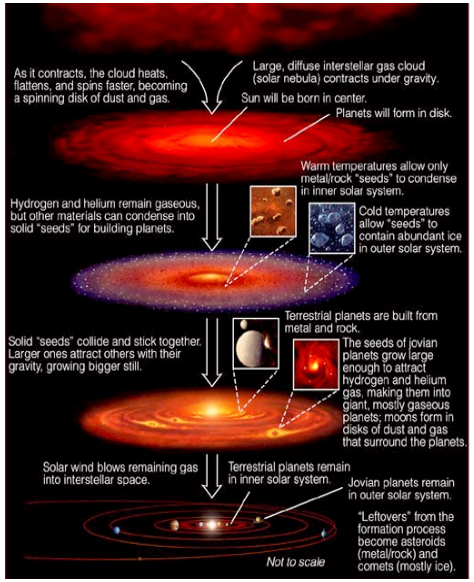
## Detection:
## 3. Transits (cont'd) –
## A highlight from *Kepler*

“Tatooine” planets, orbiting binary stars.

Fairly common: ~1% of all close binaries!




Welsh et al., 2012, Nature 481, 475




## Open issues

have to form planets in ~ few Myrs

1) how did the gas disk disperse?
2) how are planetesimals made? Are dust grains sufficiently sticky?
3) what makes chrondrules?
4) How do planetesimals survive collisions?
5) What is Jupiter's role in the fate of other planets?
6) Do giant planets only form outside frost lines? If so, how to explain the extra-solar hot Jupiters?
7)....