Searching for transiting giant extrasolar planets

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13:30- June 27, 2002

University of Tokyo,
Theoretical Astrophysics Group Seminar

Cosmology in the 20th century

- Rapid progress of cosmology since 1980's
  - existence of dark matter established
  - temperature fluctuations in the microwave background
  - measurement of the Hubble constant within 10 percent accuracy
  - detection of MACHO(Massive Compact Halo objects)
  - possibly non-zero cosmological constant
  - initial conditions of the universe from particle cosmology
- Cosmology is definitely one of the most matured fields in physical sciences at the present time.

What's next, Precision Cosmology ?

--- Since people have been working on the problem for more than sixty years, perhaps the most surprising result would be that in the next decade a consistent and believable picture for the values of the cosmological parameters is at last established. ---

P.J.E.Peebles (1993) ``Principles of Physical Cosmology''

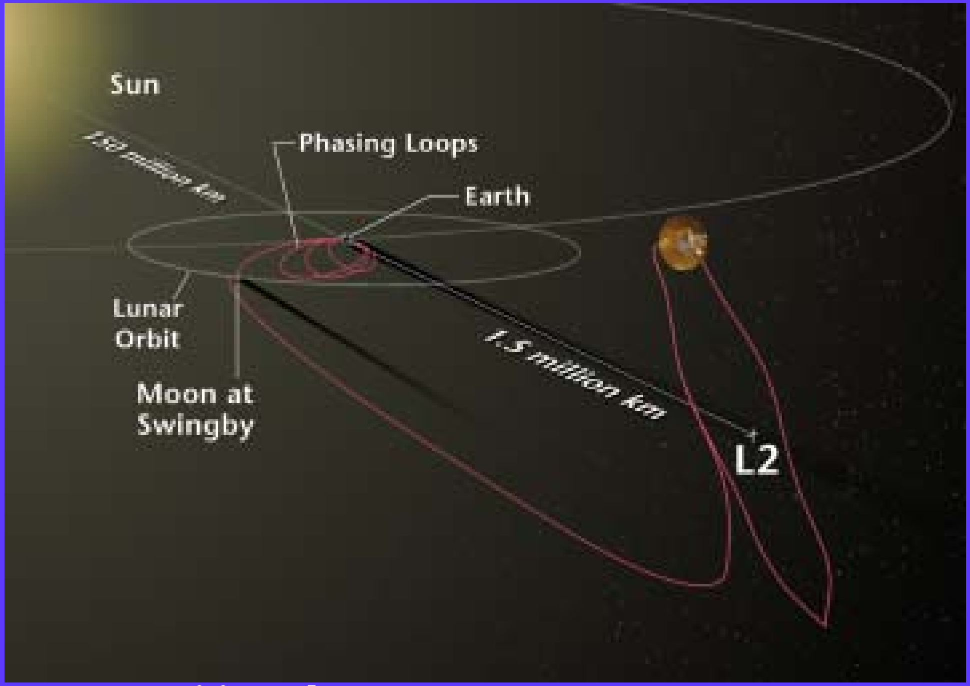
But !

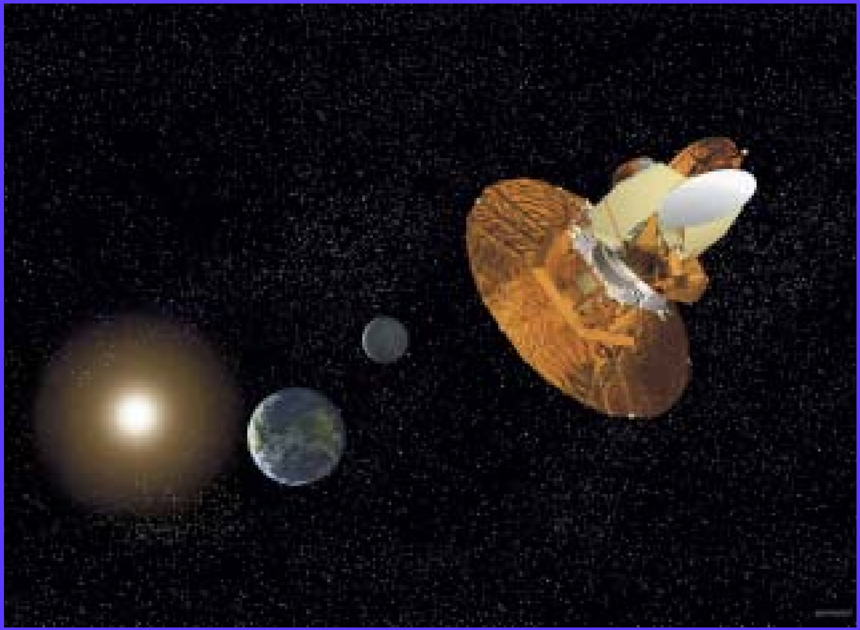
Surprisingly the values of cosmological parameters seem to have been already converged fairly well...

What's next ?

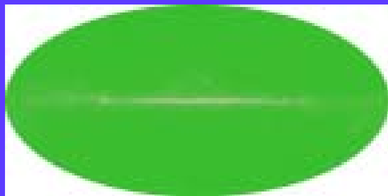
June 30, 2001, 15:46:46 EDT @Florida

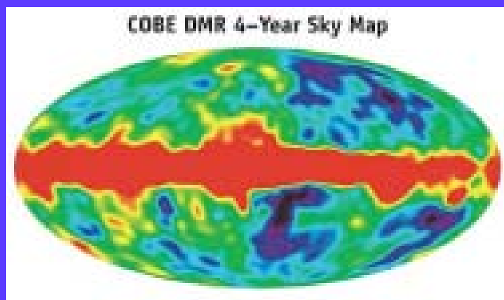
MAP launched !

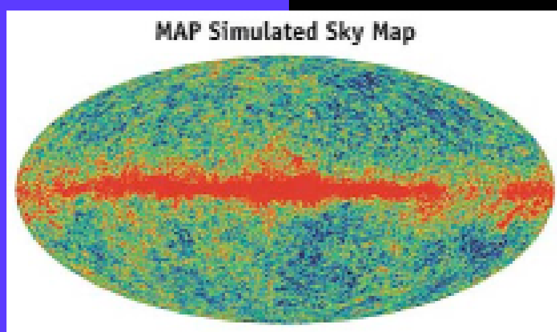


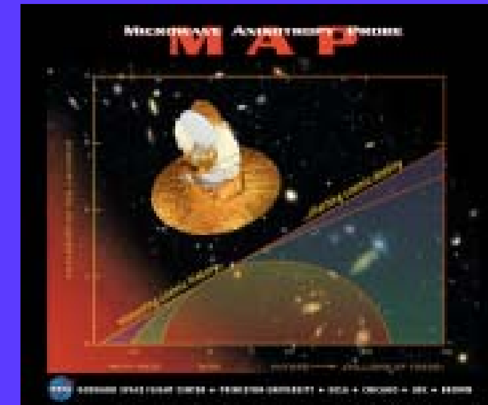


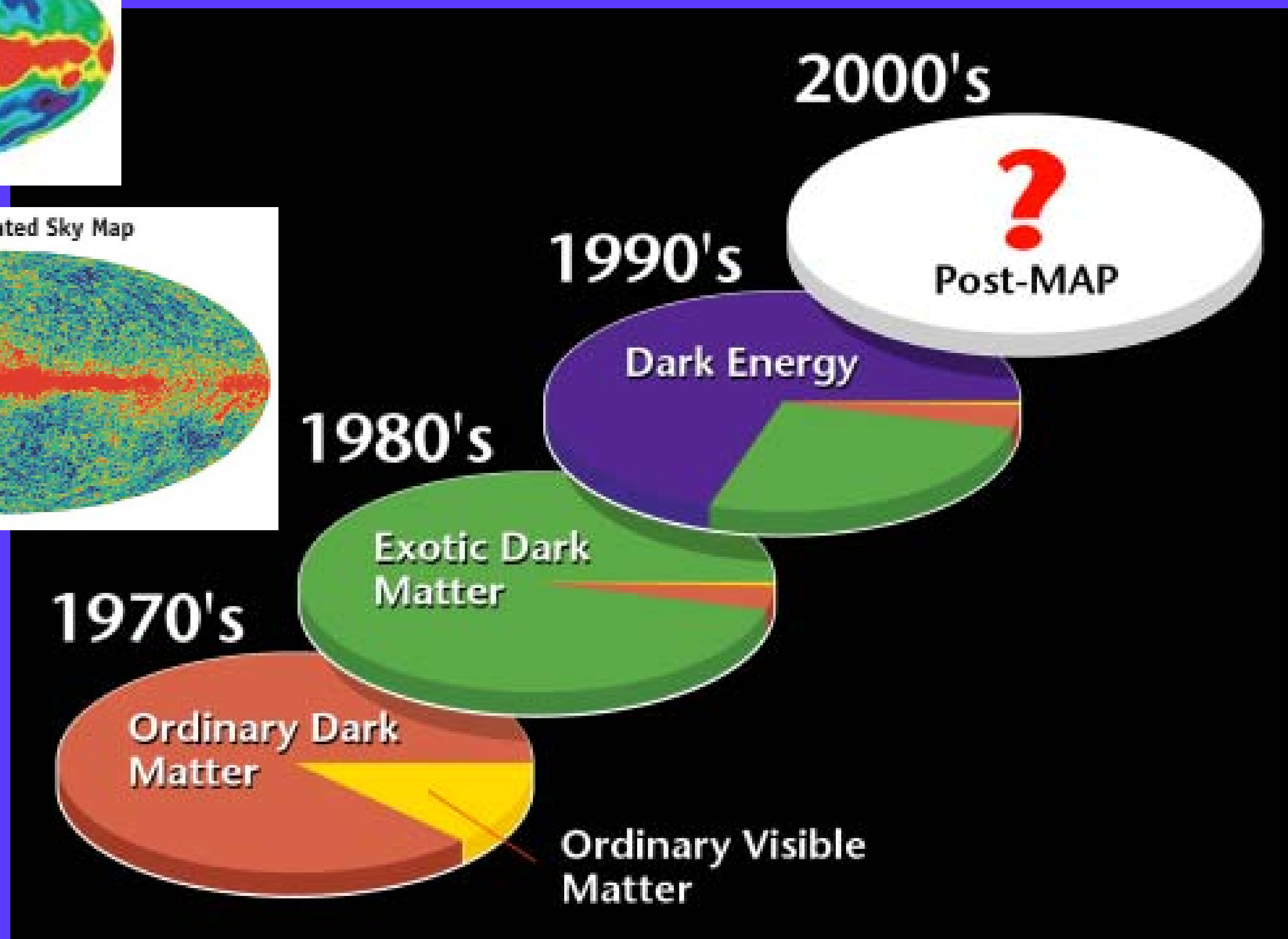
MAP Science











Transiting planets

Search for extrasolar planets !

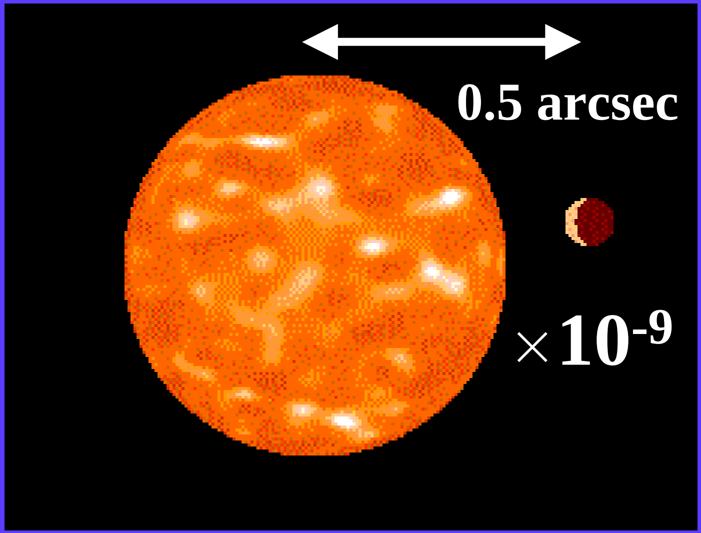
- the goal: ***Are we alone ?***
  - origin of the earth
  - origin of the Solar System
  - habitable planets ⇒ origin of life
  - signature of extra-terrestrial life ?
  - extra-terrestrial intelligence ?

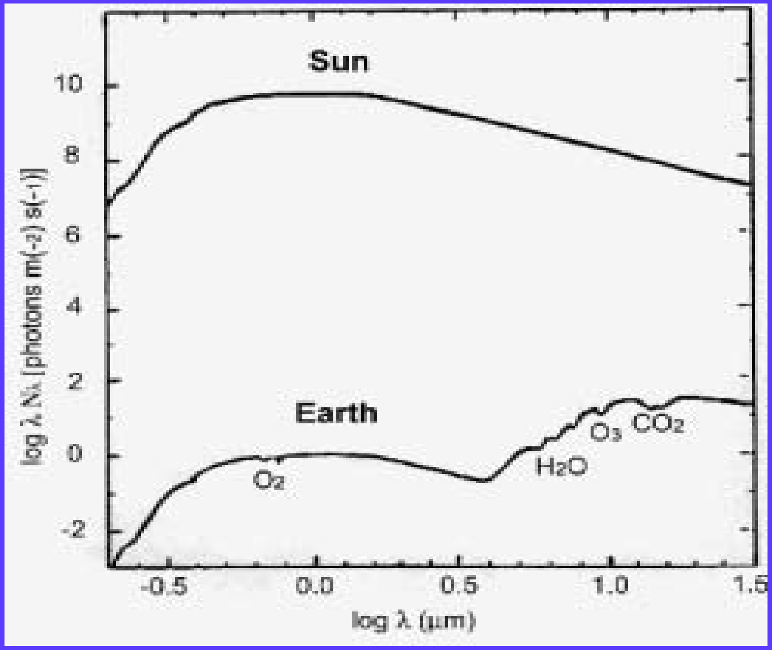
"Where are they ?" E.Fermi (1950)

Direct imaging ?

Jupiter at a distance of 10 pc

visual magnitude:　27mag
angular distance from the main star：　0.5arcsec

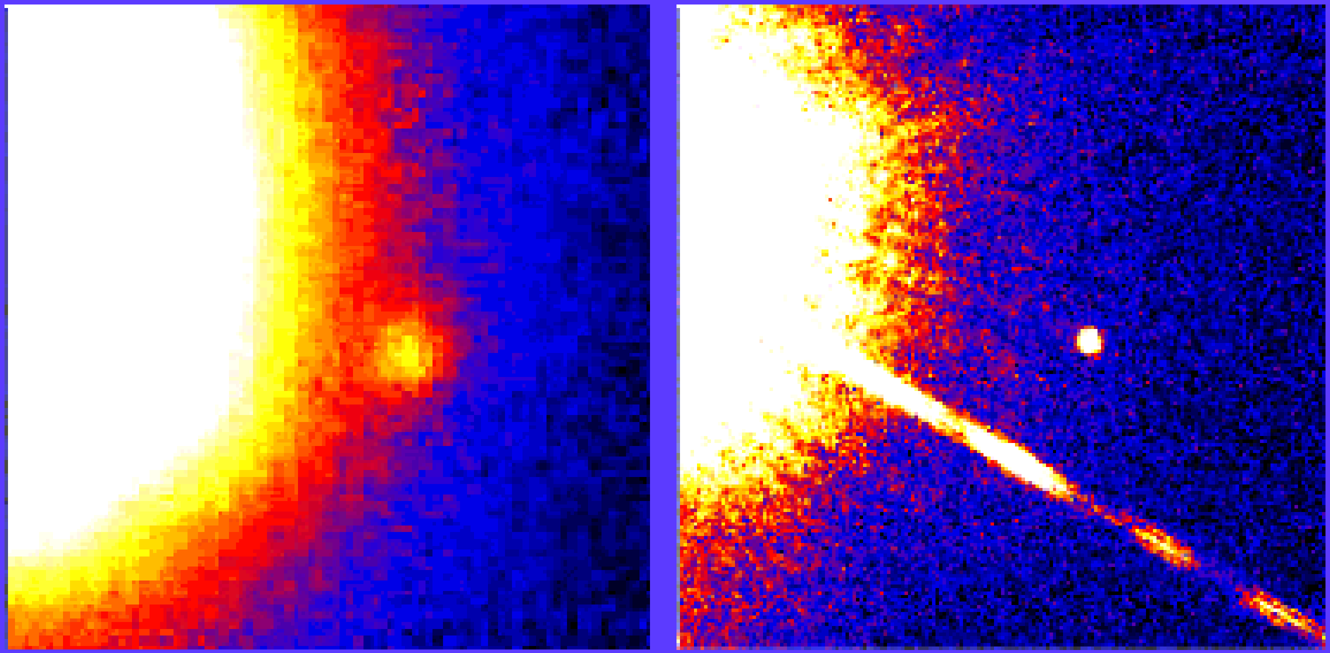




need to detect a 10^{-9} times darker object than the main star which locates within a typical seeing scale of the ground observation !

⇒ Just impossible！

An observed brown dwarf: Gliese 229b



Gliese229 b:

angular separation
7 arcsec

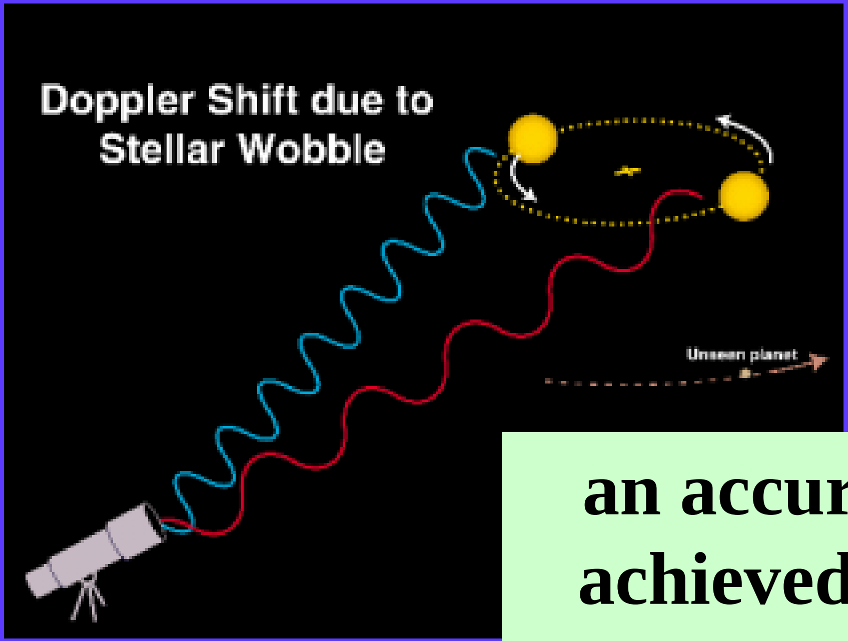
luminosity ratio
5000

left : Palomar
right : HST
(T.Nakajima)

- Consider Jupiter seen at a distance of 10pc:
  14 times closer to the star
  1/200,000 darker than the above example !

Radial velocity of a star perturbed by a planet

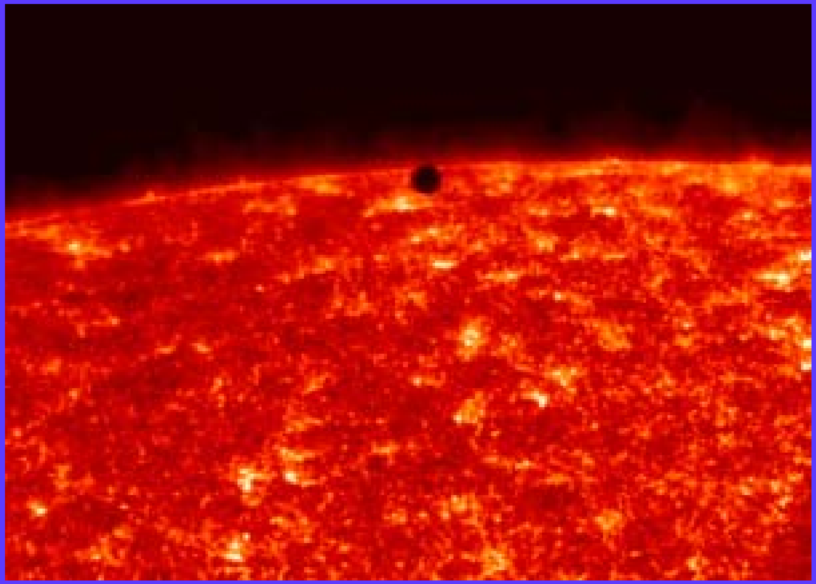
Even if one cannot directly observe a planet, one can infer its presence indirectly from the measurement of the motion of the main star.



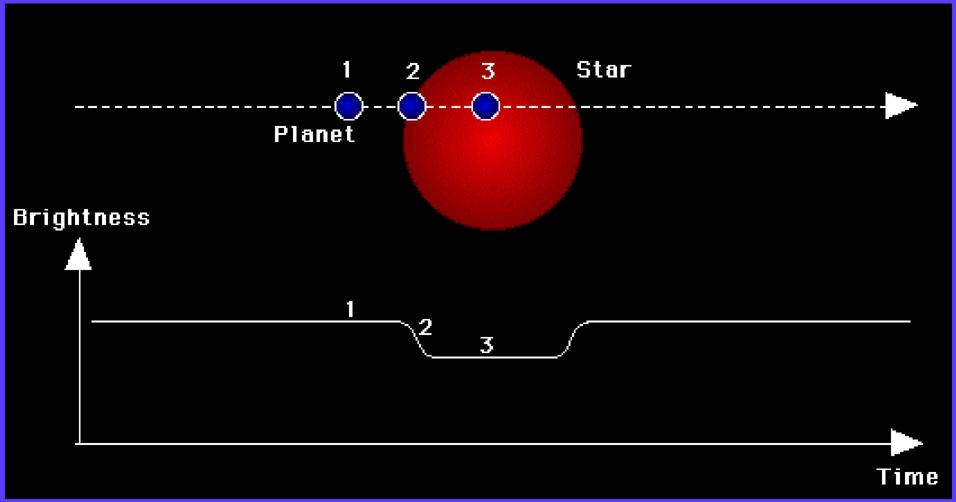
e.g., velocity modulation of the Sun due to a planet
12.5 m/s (Jupiter)
0.1 m/s (Earth)

an accuracy of 3m/s is already achieved from the ground obs.
⇒ the current major method in search for Jupiter-sized planets

Occultation of the main star due to the transit of a planet



Mercury across the Sun
(TRACE satellite: Nov. 1999)



probability of the transit: **0.3%** $(AU/a_{orbit})(R_{star}/R_{Sun})$

flux variation: **1%** $(R_{planet}/R_{Jupiter})^2(R_{Sun}/R_{star})^2$

$\Leftrightarrow$ **photometry accuracy in the ground obs. > 0.1%**

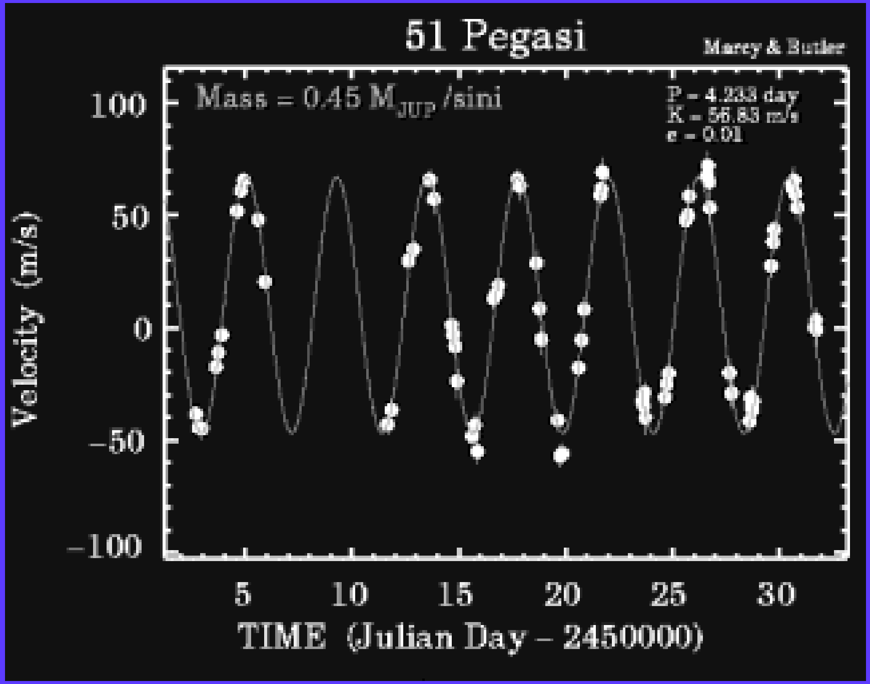
Brief history of the discovery of extrasolar planets

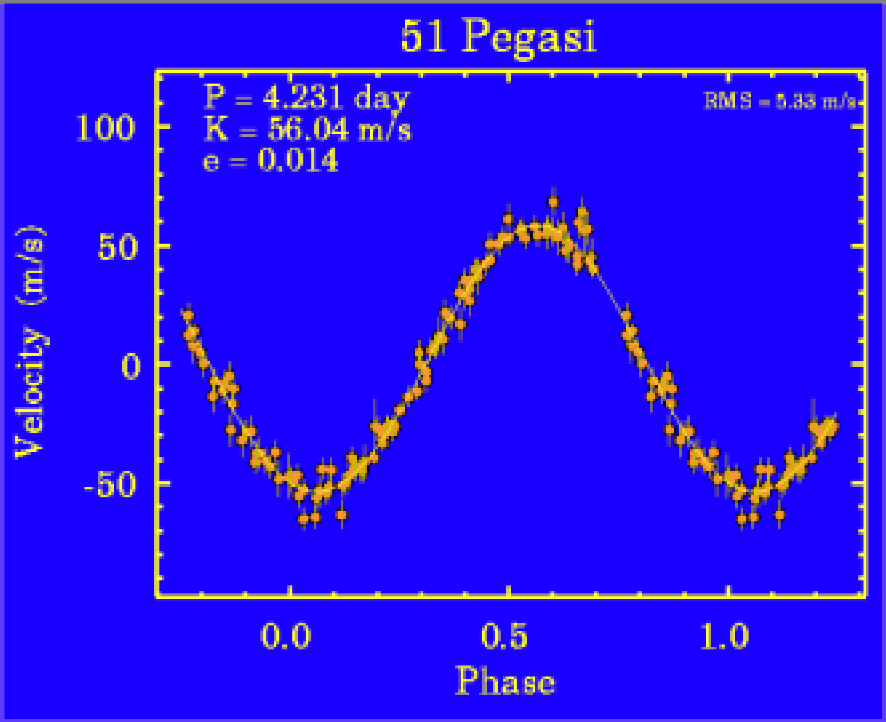
- **1992:** three planets around PSR1257-12 (Wolszczan & Frail)
- **1995:** a planet around the main sequence star 51 Pegasi (Mayor & Quelos)
- **1999:** transit of a planet around HD209458 (Charbonneau et al., Henry et al.)
- **2001:** discovery of Na in the atmosphere of HD209458b
- ***91 extrasolar planets*** are reported (June, 2002)

http://exoplanets.org/

51Pegasi b: a first discovered planet around a main-sequence star

- discovered from the periodic change of the radial velocity of the main star (Mayor & Queloz 1995)

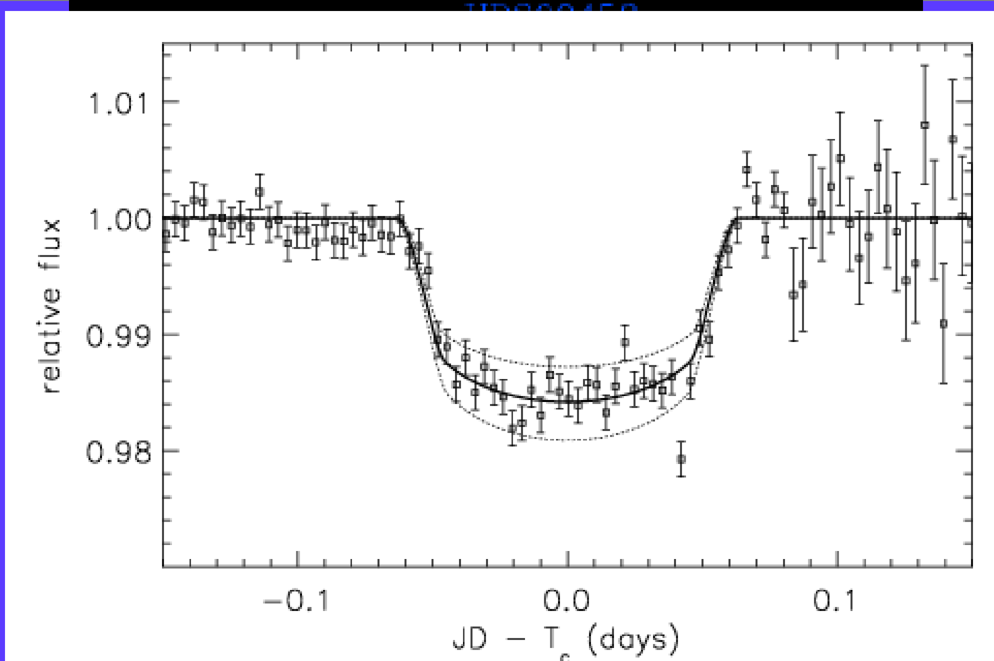


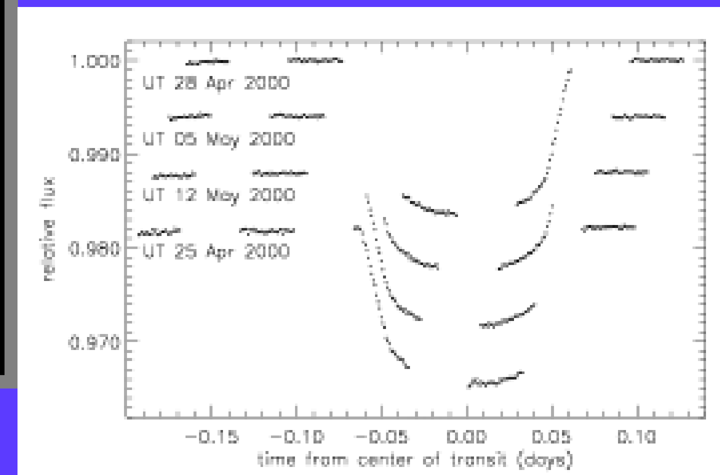


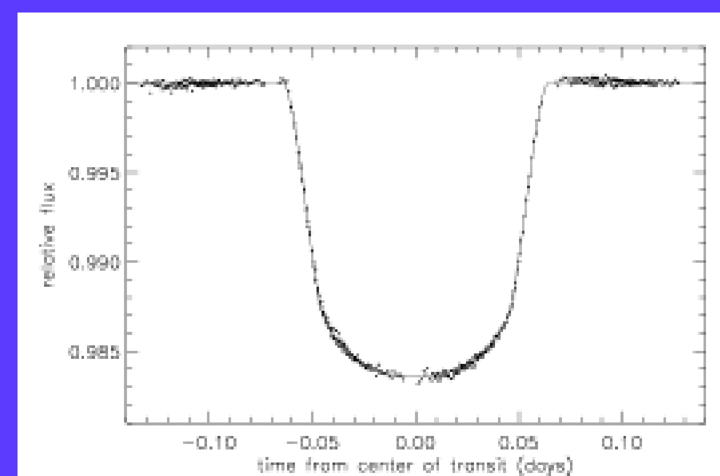
<u>P=4.2 days !</u>

a first discovery of the transit of a planet: occultation in HD209458

- detection of the change of flux of the star at the predicted phase from the velocity measurement (Charbonneau et al. 2000, Henry et al. 2000)



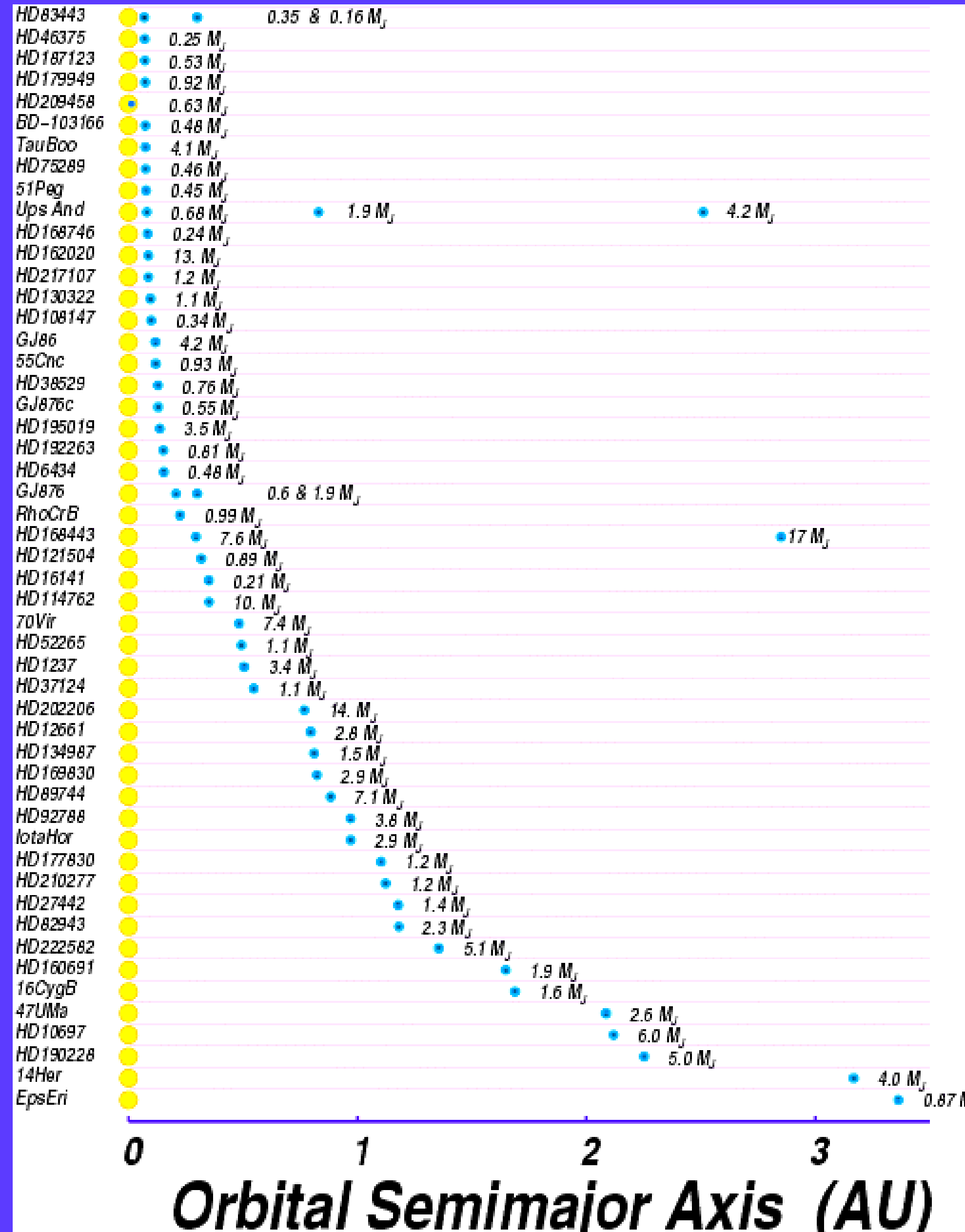




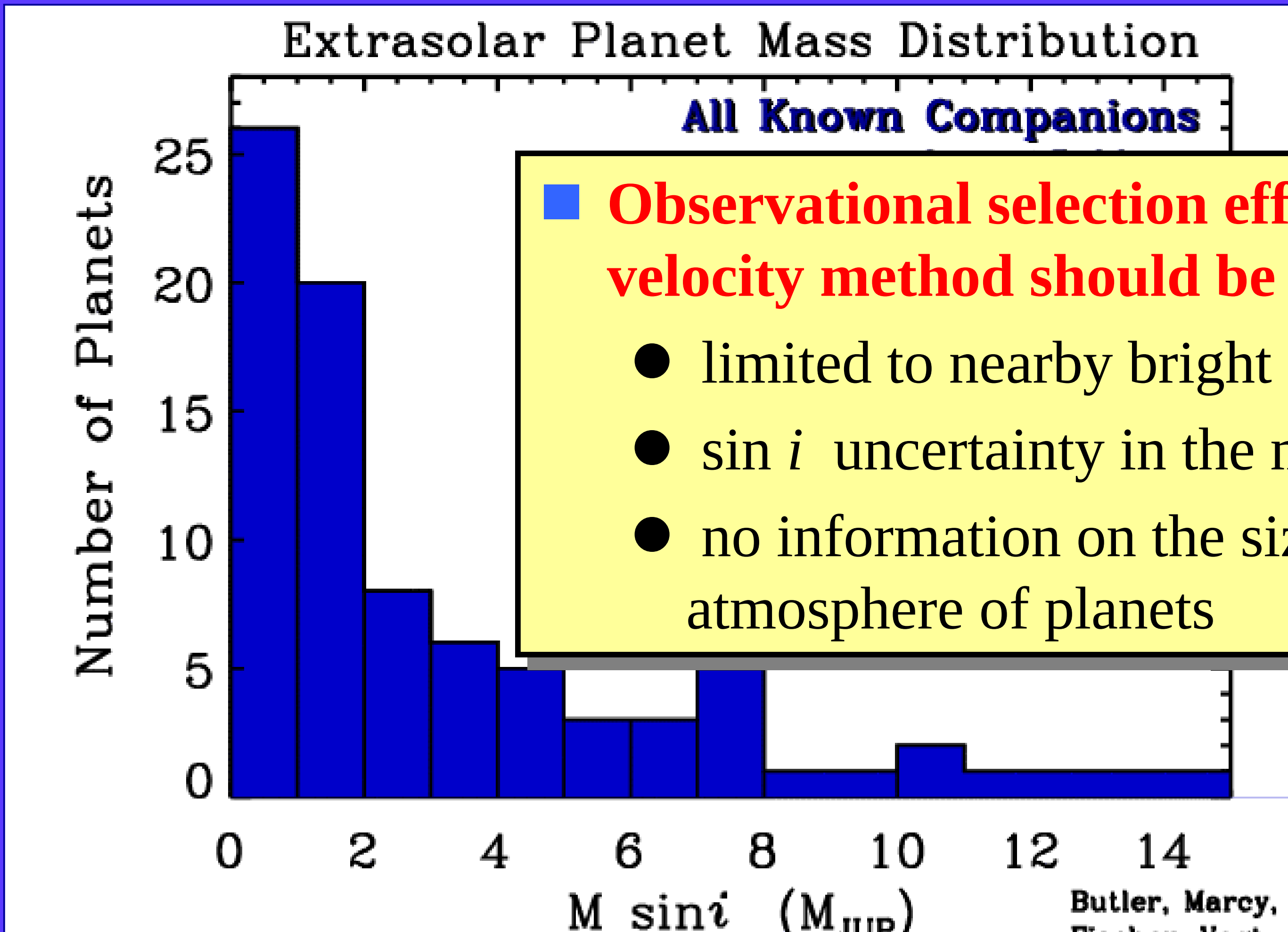
Brown et al. (2001)

A list of discovered extrasolar planets

- many Jupiter-mass extrasolar planets exist !
- their orbital radii are much smaller than predicted before.



mass function of extrasolar planets observed with the radial velocity method

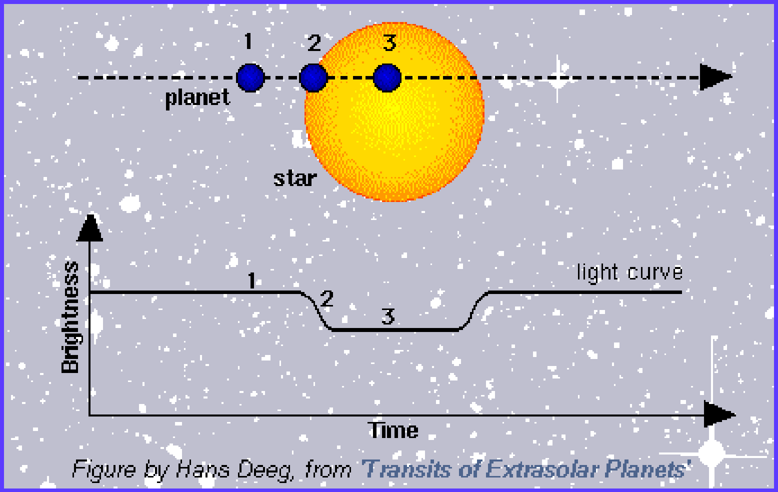


- **Observational selection effect of the radial velocity method should be significant !**
  - limited to nearby bright stars
  - sin *i* uncertainty in the mass estimate
  - no information on the size and atmosphere of planets

http://exoplanets.org/

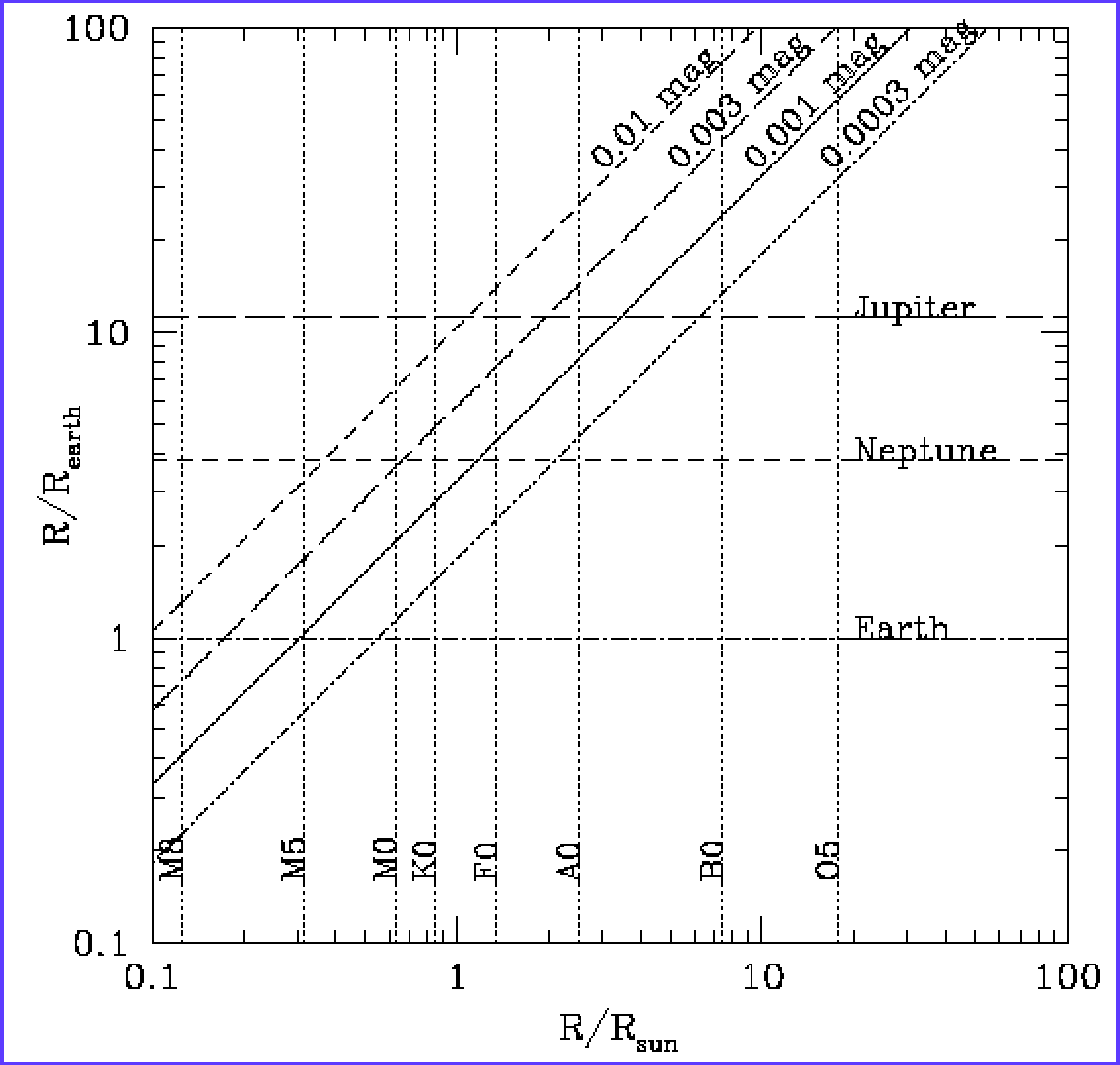
Marcy, Butler, Fischer & Vogt (2000)

Transit method for the extrasolar planet search



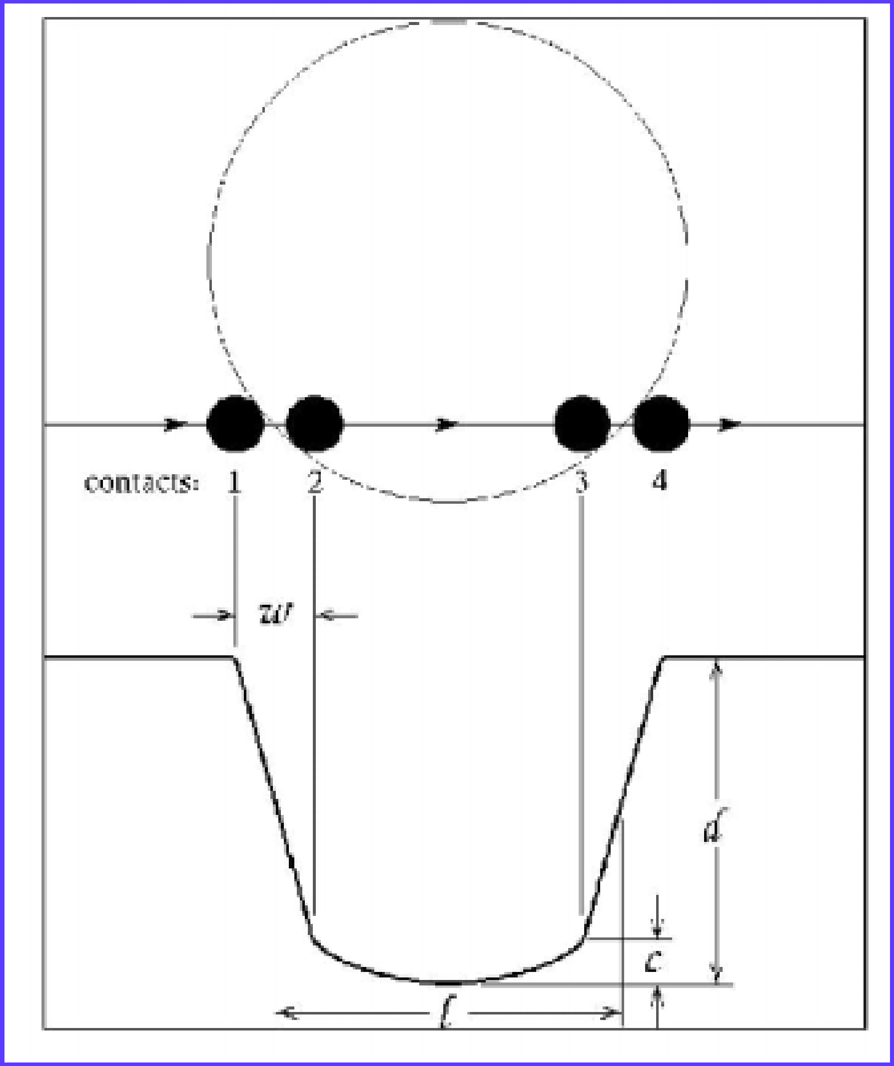
- inclination angle is determined (or only observable for edge-on system, i.e., when i ~ 90 deg.)
- size of the planet can be estimated
- complementary to the radial velocity method
- Low probability: **10% (0.05AU/a_{orbit})(R_{star}/R_{Sun})**
- Small flux variation: **1% (R_{planet}/$R_{Jupiter}$)^2(R_{Sun}/R_{star})^2**
- Sensitive to the CIGP (close-in-giant-planets)

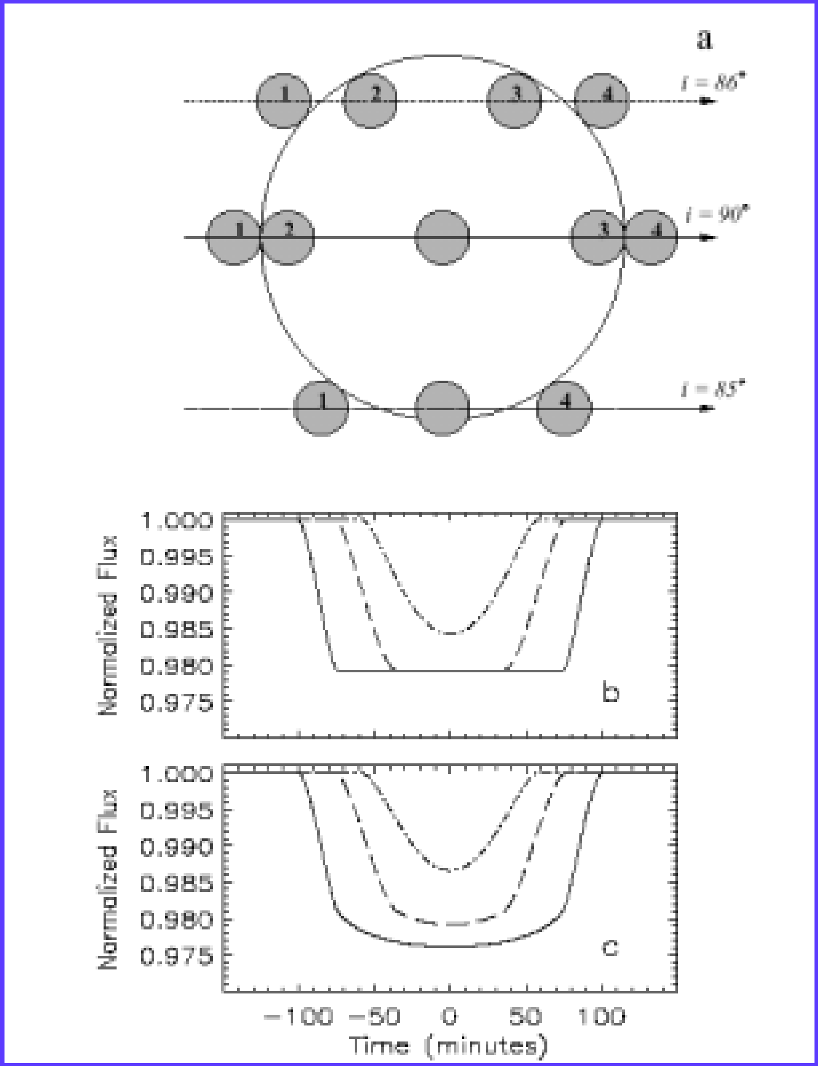
Expected depth of the transit



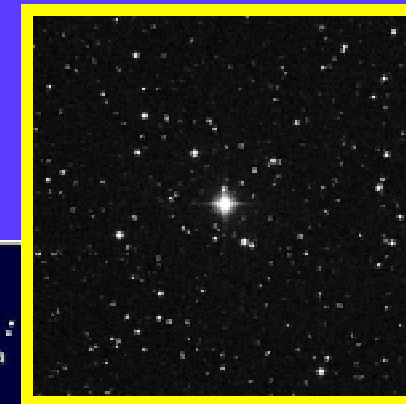
- For F-G type stars and Jupiter-size planets, the transit leads to a (0.1-1)% dimming of the main stars.
- More efficient for smaller stars like M-dwarfs unlike the radial velocity method
- Detection of earth-size planets with the transit method requires (0.01-0.001)% accurate photometry

Limb Darkening

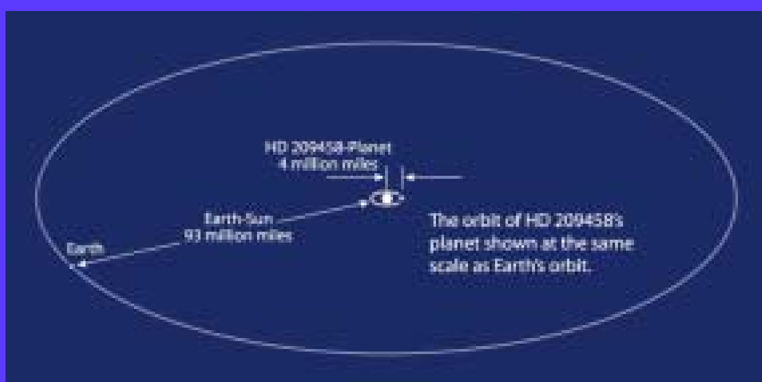


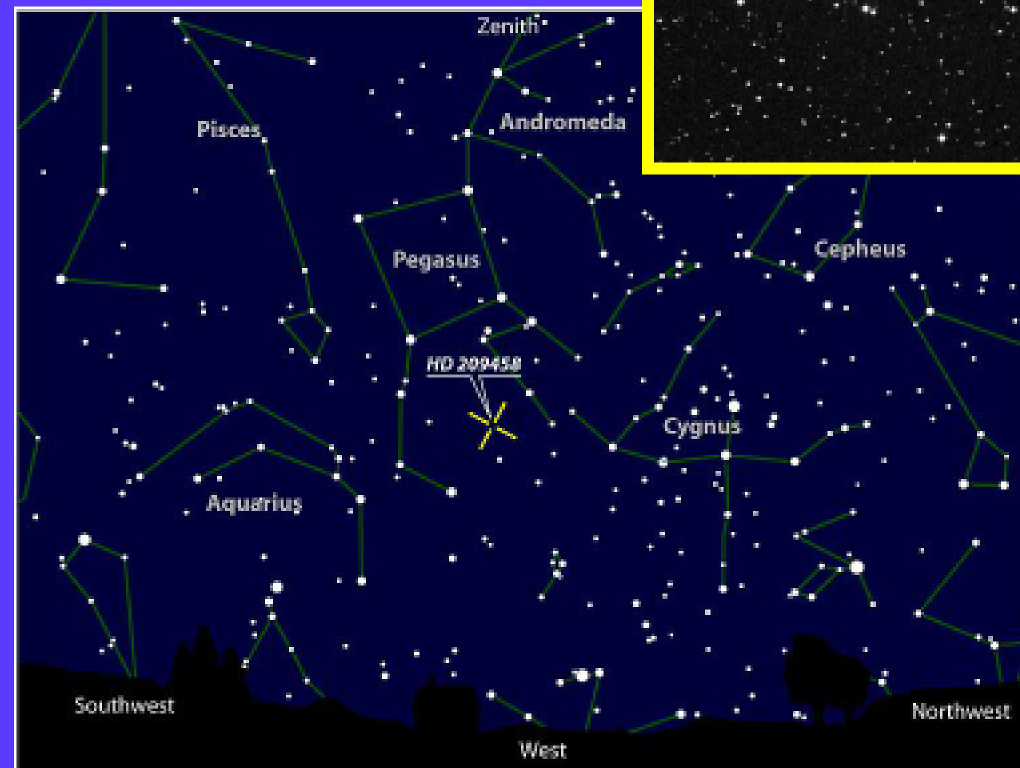


HD209458: the unique star with a transit planet



- V=7.65
- G0V
- d=47pc



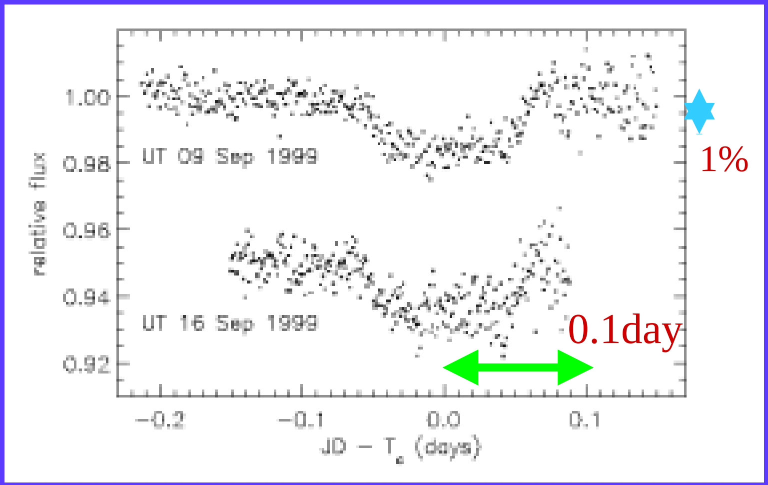


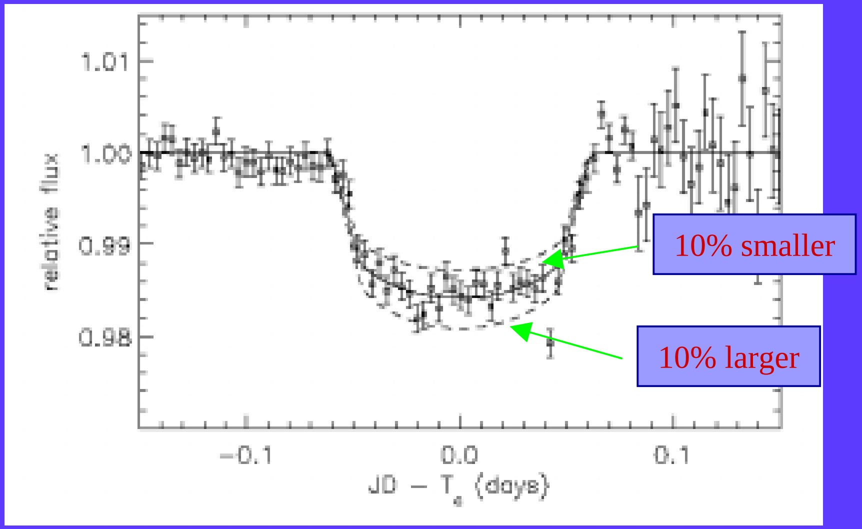
The sky at about 9:00p.m. local time in early December, facing toward the west

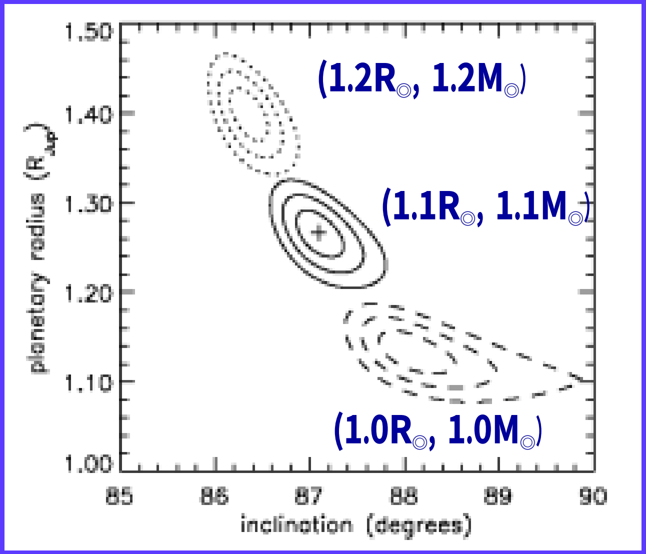
Detection of Planetary Transits Across a Sun-like Star

Charbonneau, D., Brown, T.M., Latham, D.W., & Mayor, M.
2000, ApJL, 529, L45

Light curve of HD209458







Fitting parameters: Rs, Ms, c_λ, R_p, *i*

C_λ limb darkening parameter $B_\lambda(\mu)=1-c_\lambda(1-\mu)$

Rs, Ms, c_λ estimated from stellar model (metallicity, temperature, color, luminosity)

Henry et al. 1999 (IAU Circ. 7307)
Henry et al. 2000 ApJ, 529, L41
Charbonneau et al. (2000)

parameters for the HD209458 system

Table 1: Orbital Solution for HD 209458.

Period	3.52433 ± 0.00027	days
γ	-14.7652 ± 0.0016	$\mathrm{km\,s^{-1}}$
K	85.9 ± 2.0	$\mathrm{m\,s^{-1}}$
e	0	FIXED
T_c	$2,451,430.8238 \pm 0.0029$	HJD
$M_p \sin i$	$0.685 \pm 0.018\ (M_*/1.1M_\odot)^{2/3}$	M_{Jup}

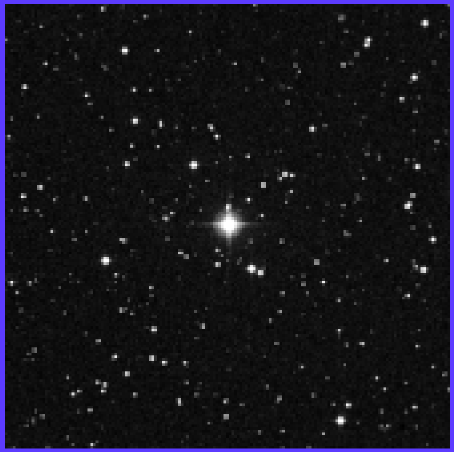
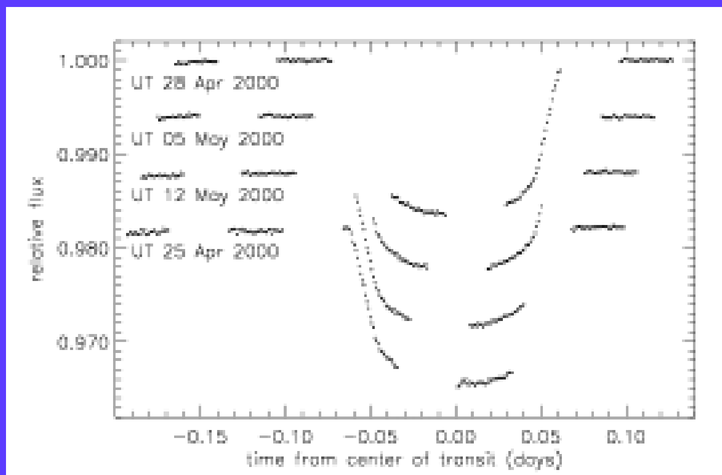
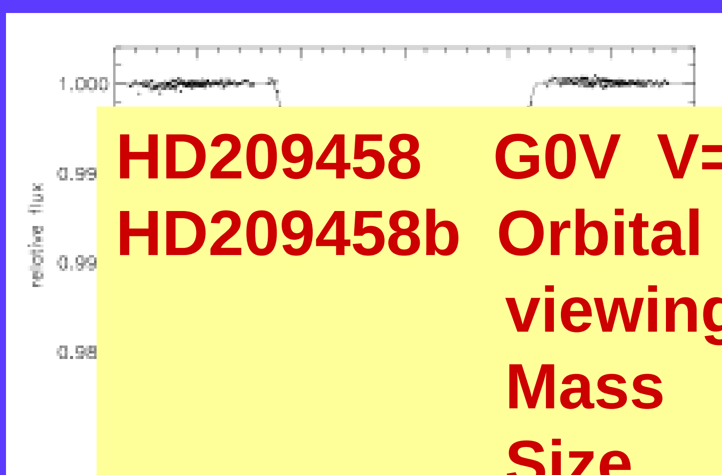


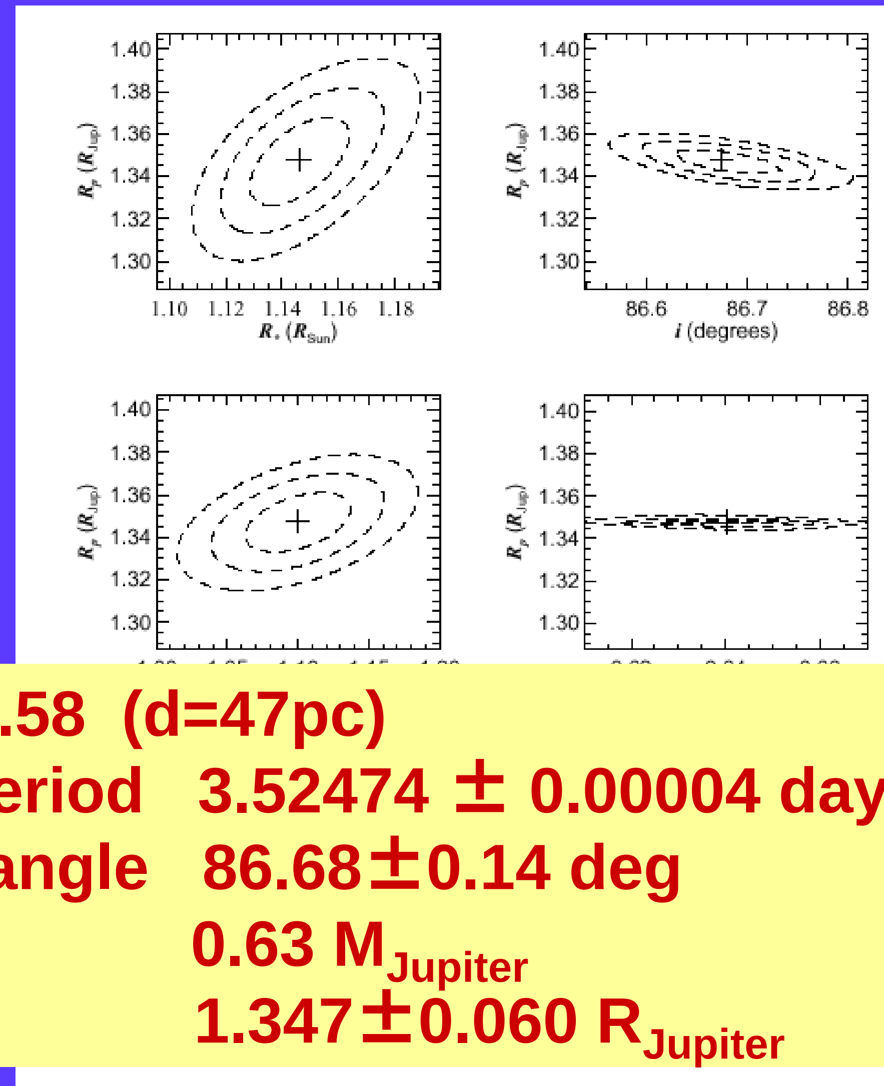
Table 2: The Mass and Radius of HD 209458

Model			$\log g$ vs. $T_{\rm eff}$			M_V vs. $B-V$		
Code	Z	Y	Age (Gyr)	M_* ($M_\odot$)	R_* ($R_\odot$)	Age (Gyr)	M_* ($M_\odot$)	R_* ($R_\odot$)
Geneva	0.02	0.30	4.6	1.15	1.33	6.3	1.08	1.29
Bertelli	0.02	0.27	5.0	1.11	1.31	4.0	1.09	1.30
Claret	0.02	0.28	5.3	1.12	1.31	7.9	1.05	1.27
Yale	0.02	0.27	5.7	1.11	1.31	7.3	1.06	1.28
Yale	0.02	0.30	6.0	1.05	1.27	7.7	1.01	1.25
Geneva	0.008	0.264	9.8	0.94	1.20	12.3	0.91	1.30

HST observation of HD209458







HD209458 G0V V=7.58 (d=47pc)

HD209458b Orbital Period 3.52474 ± 0.00004 days

viewing angle 86.68±0.14 deg

Mass $0.63\ M_{Jupiter}$

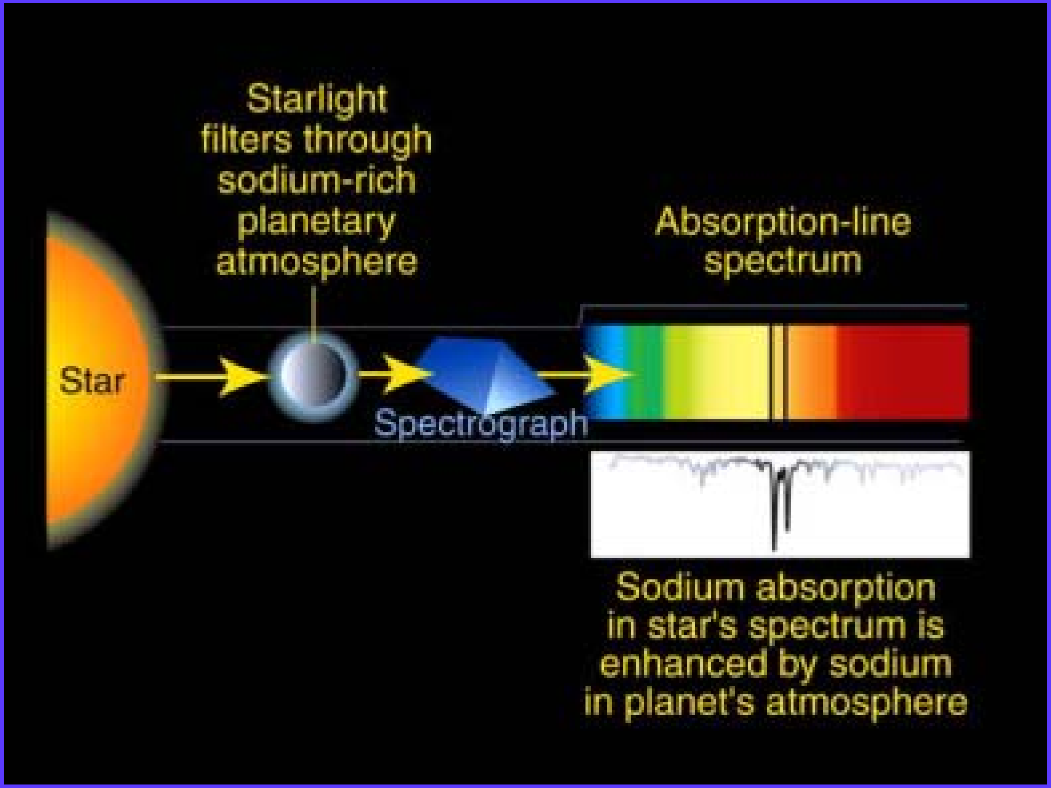
Size $1.347 \pm 0.060\ R_{Jupiter}$

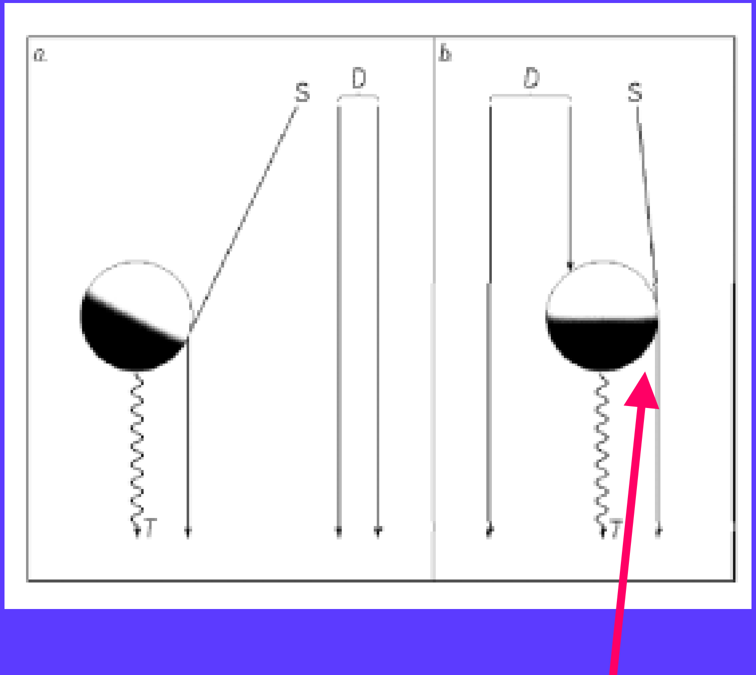
Implications of HD209458b

HD209458 G0V V=7.58 (d=47pc)
HD209458b Orbital Period 3.52474 ± 0.00004 days
viewing angle 86.68±0.14 deg
Mass 0.63 $M_{Jupiter}$
Size 1.347±0.060 $R_{Jupiter}$

- M_p=0.63 M_J, R_p=1.3 R_J :roughly consistent with a theoretical model for CIGP (e.g., Guillot et al. 1996)
- ρ =0.4 g/cm^3 < Saturn's density
- g=970 cm/s^2
- Tp = 1400(1-A)1/4 K A:albedo Ts=6000K
- $v_{thermal}$ ~ 6 km/s < 42 km/s=v_{escape}

Detection of an extrasolar planet atmosphere



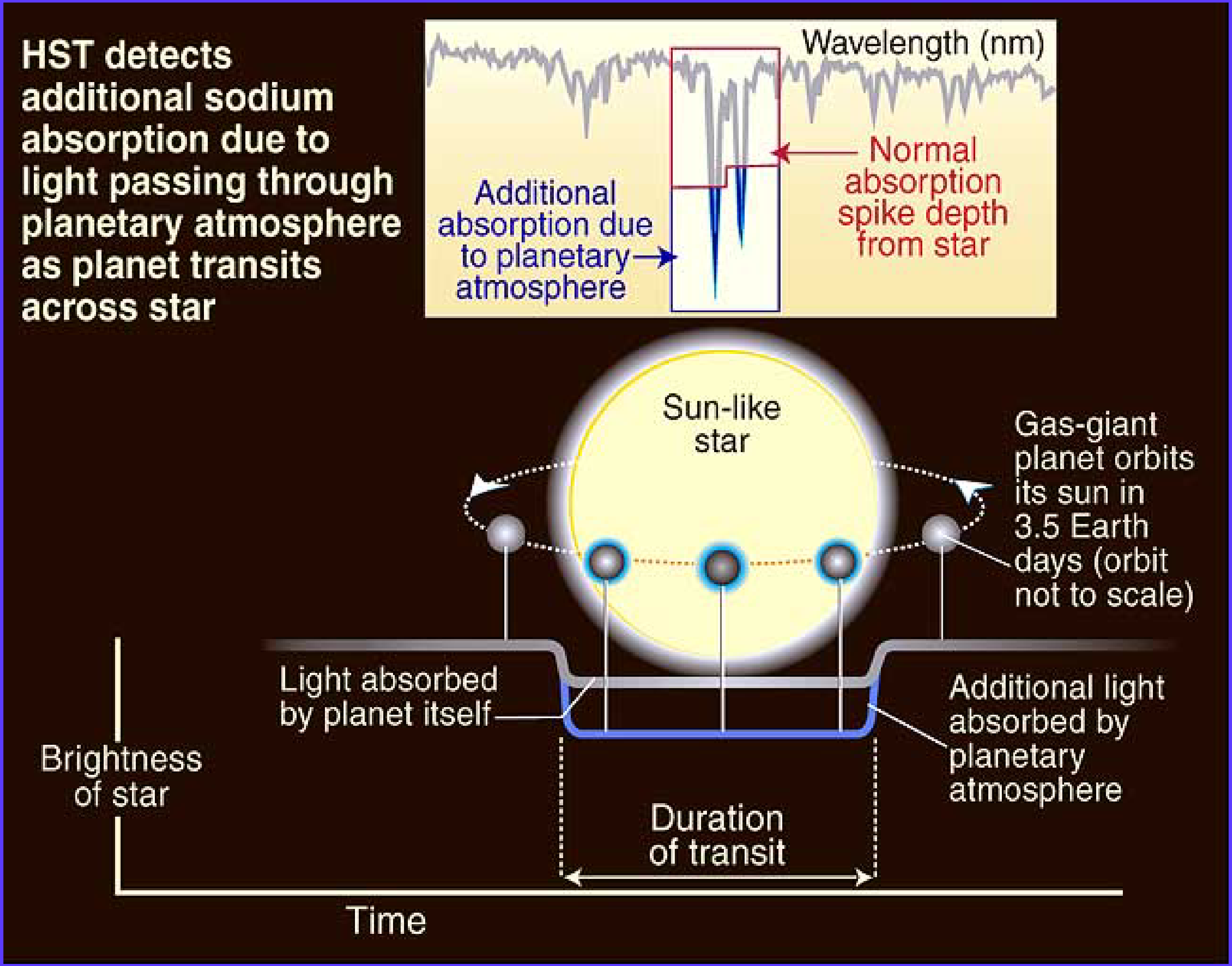


Absorption due to the planetary atmosphere

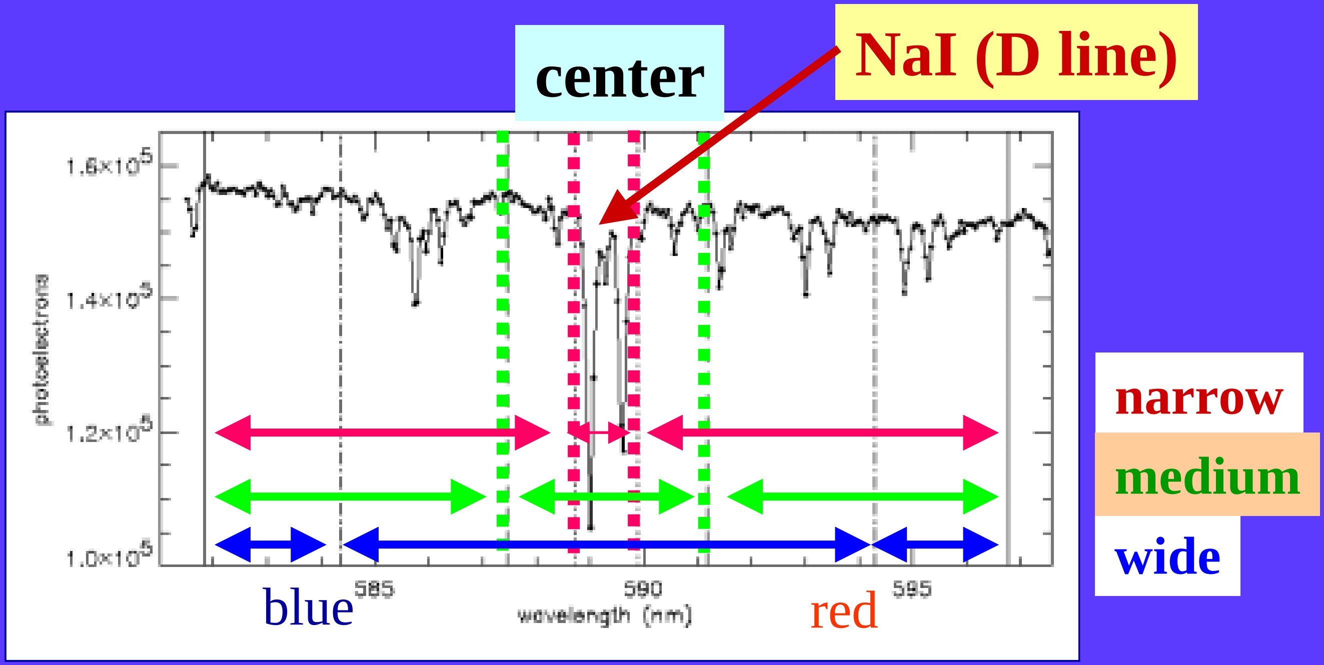
Charbonneau, D., Brown, T.M., Noyes, R.W., & Gilliland, R.L. 2002, ApJ, 568, 37

S: scattered light
D: direct light
T: thermal radiation

Schematic detection method of atmospheric absorption



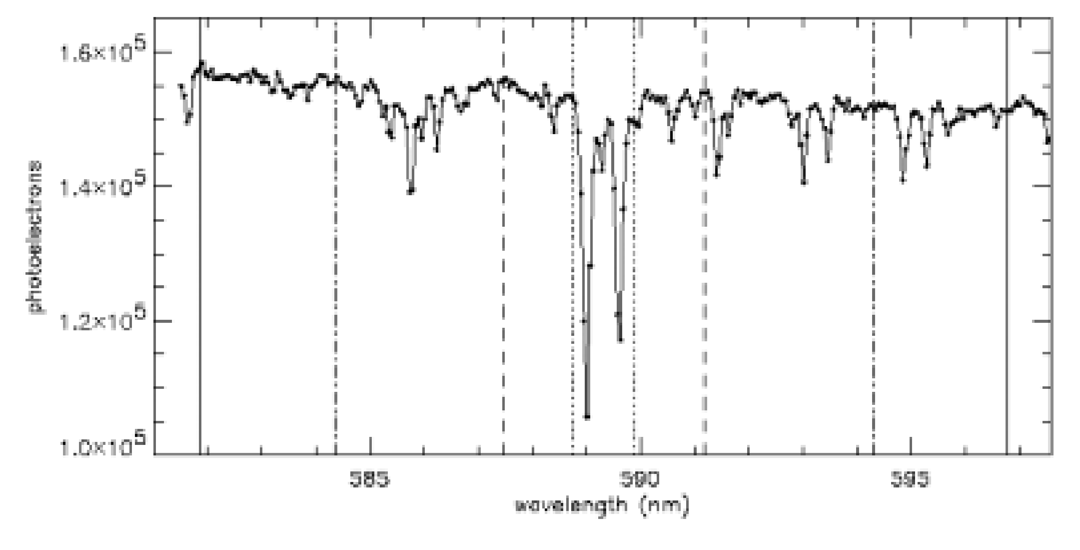
HST spectrum for HD209458



width	blue (nm)	center (nm)	red (nm)
narrow	n_b: 581.8–588.7	n_c: 588.7–589.9	n_r: 589.9–596.8
medium	m_b: 581.8–587.4	m_c: 587.4–591.2	m_r: 591.2–596.8
wide	w_b: 581.8–584.3	w_c: 584.3–594.3	w_r: 594.3–596.8

Detection of additional Na absorption

HST spectrum



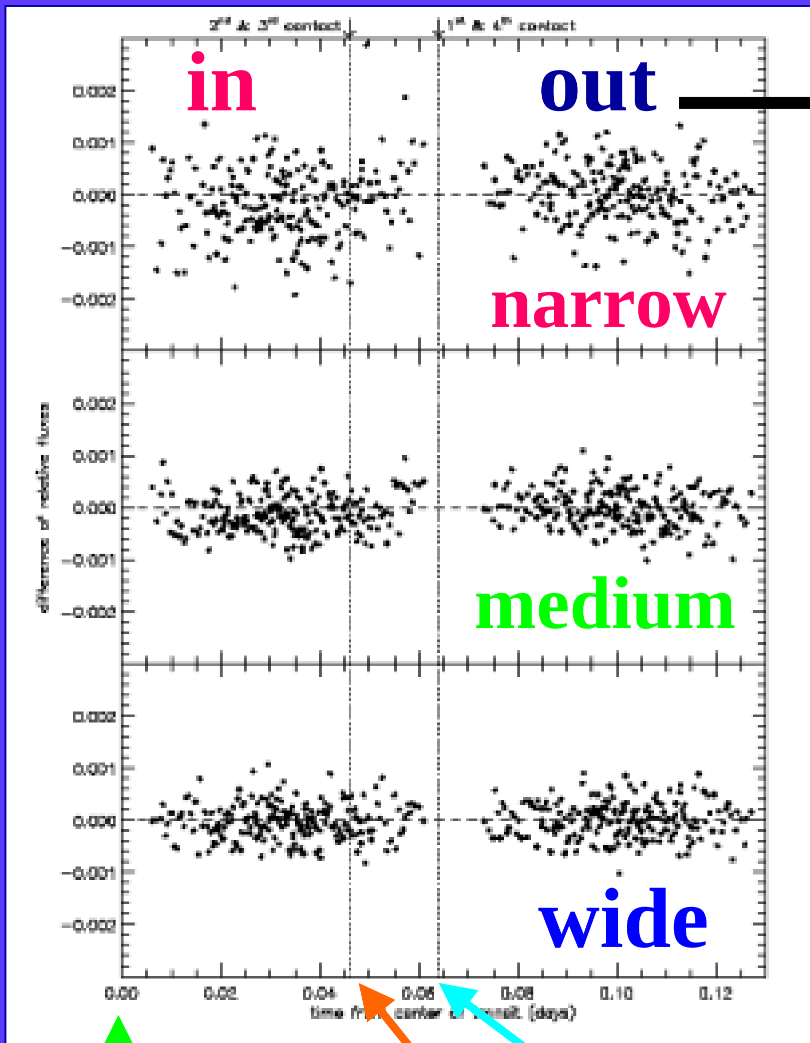
absorption index

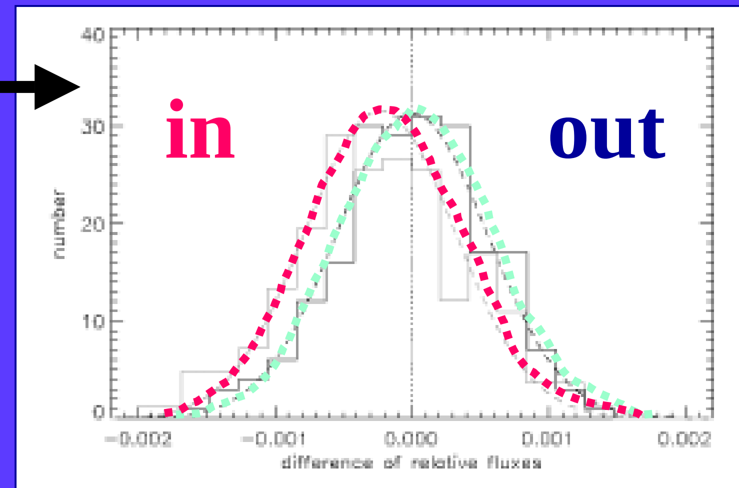
$$
\begin{aligned}
n_{Na}(t) &= n_c(t) - [n_b(t) + n_r(t)] / 2 \\
m_{Na}(t) &= m_c(t) - [m_b(t) + m_r(t)] / 2 \\
w_{Na}(t) &= w_c(t) - [w_b(t) + w_r(t)] / 2.
\end{aligned}
$$

$$
\begin{aligned}
\Delta n_{Na} &= \overline{n_{Na}(t_{in})} - \overline{n_{Na}(t_{out})} = (-23.2 \pm 5.7) \times 10^{-5} \\
\Delta m_{Na} &= \overline{m_{Na}(t_{in})} - \overline{m_{Na}(t_{out})} = (-13.1 \pm 3.8) \times 10^{-5} \\
\Delta w_{Na} &= \overline{w_{Na}(t_{in})} - \overline{w_{Na}(t_{out})} = (-\ 3.1 \pm 3.6) \times 10^{-5}.
\end{aligned}
$$

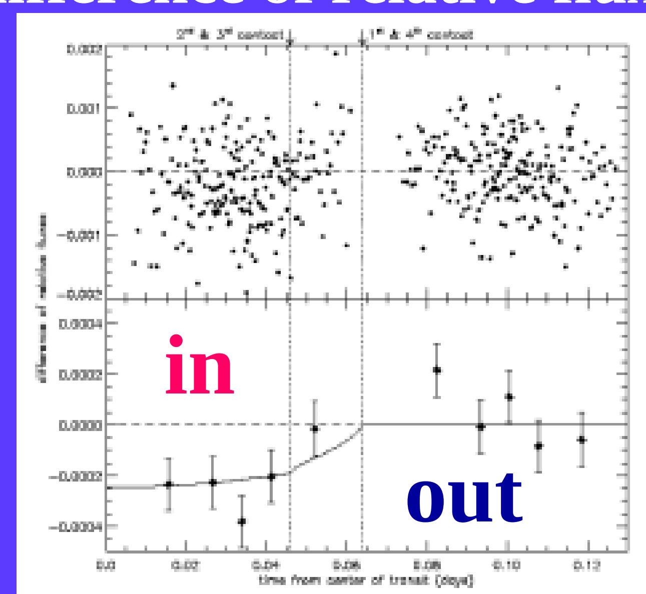
Large difference between in- and out-of-transits for the region around the Na line !

Flux distribution at in- and out-of-transits for HD209458





difference of relative fluxes



Central transit time

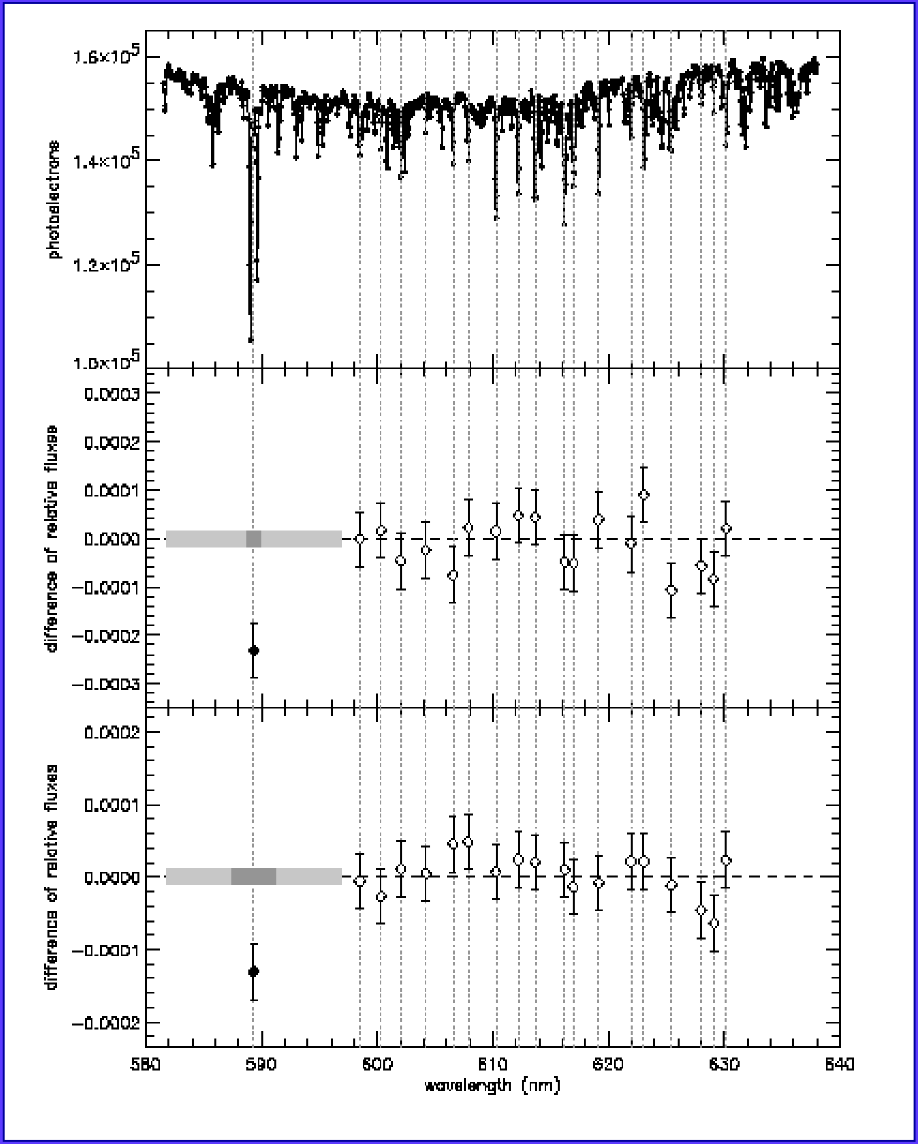
1st and 4th contact

2nd and 3rd contact

Transiting planets

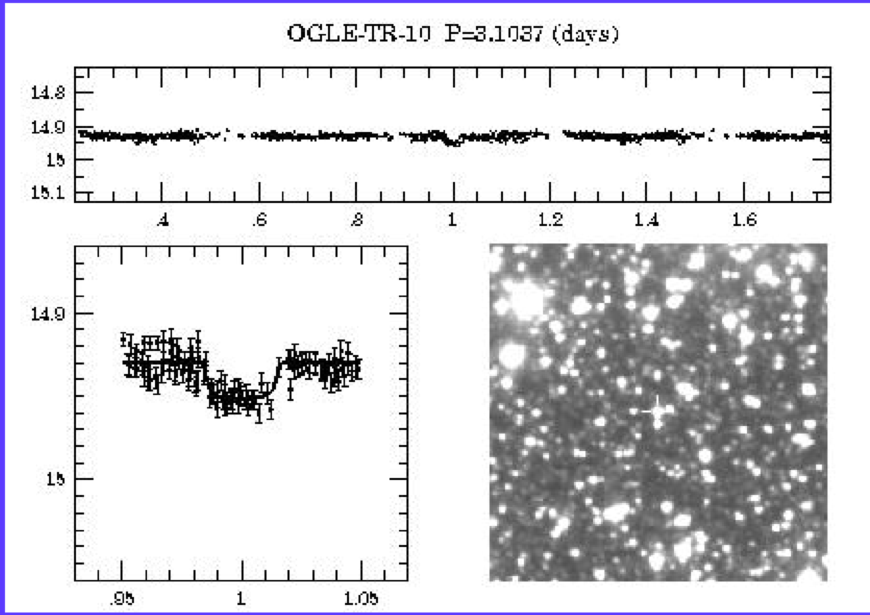
Detected only for the Na line wavelengths

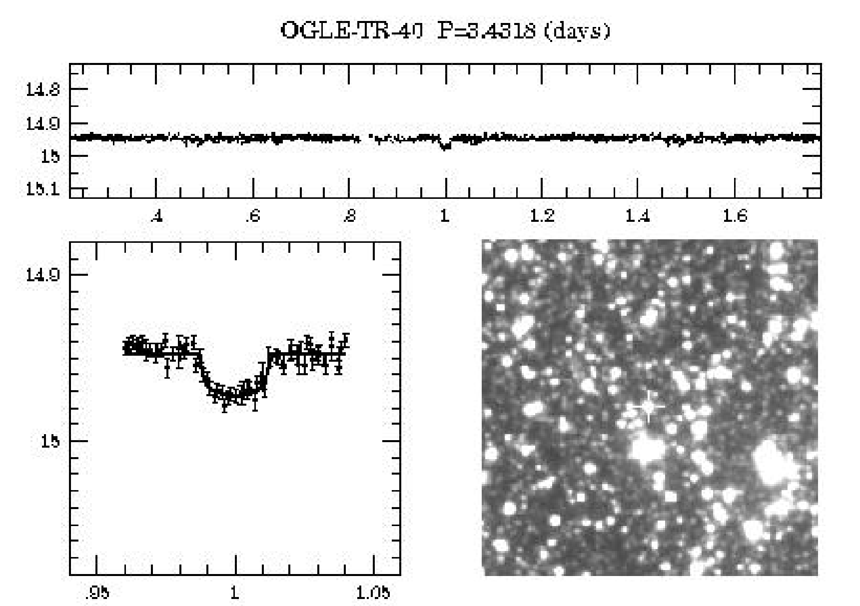
difference of relative fluxes



Transit surveys：OGLE III

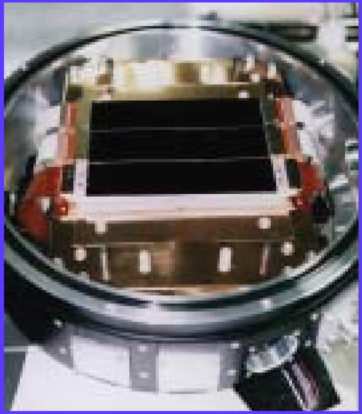
- Optical gravitational lensing experiment III
- V and I bands with 2k✕4k✕8CCD chips
- <1.5% photometric accuracy for 52000 Galactic disk stars
  - ***185 transits for 46 objects (in 45 days+follow-up)***
  - ***2 cases for Jupiter-size planets ?***





Deep Transit Search with Subaru Suprime Cam

- The first attempt of deep transit planet search with Subaru 8m telescope + wide-field camera (Suprime-Cam) on September 27 and 28, 2002
- T.Yamada (P.I: NAOJ), Y.Suto (co.I.: U.Tokyo), E.L.Turner (co.I: Princeton U.), et al.



Goals of the transit survey

1. Frequency of Close-In Extrasolar Planets
2. Size Distribution of Close-In Extrasolar Planets
3. Distribution of the Orvital Period of Close-In Extrasolar Planets
4. Search for Close-In Extrasolar Planets among Multiple Stars
5. Properties of the Stars that have Close-In Extrasolar Planets
6. Provide Basis of the Future Space Missions

Our strategy

- Deep transit survey at low galactic latitude field using Suprime Cam.
- monitor 1-2 selected fields for ~ 10 days in total.
- With auto-guiding, we repeat 10-30 sec exposures and repeat relative aperture photometric for ~100000 stars in the suitable magnitude range.
- optimized strategy to detect CIGP with orbital period of 2-3 day; 1-2 % decrement of brightness for the giant planet around F-G type stars or earth-size planet around M type stars (c.f., 1.5% for HD209458).

expected number of transits

number of stars of radius R_*

geometrical probability for the transit

$$N_p = \iiint \underline{N(R_*)}\,\underline{P_p(R_p, a \mid R_*)}\,\underline{\left(\frac{R_*}{a}\right)}\,\underline{P_{vis}(t_T, T_{orbit}, \delta m)}\,dR_*\,dR_p\,da$$

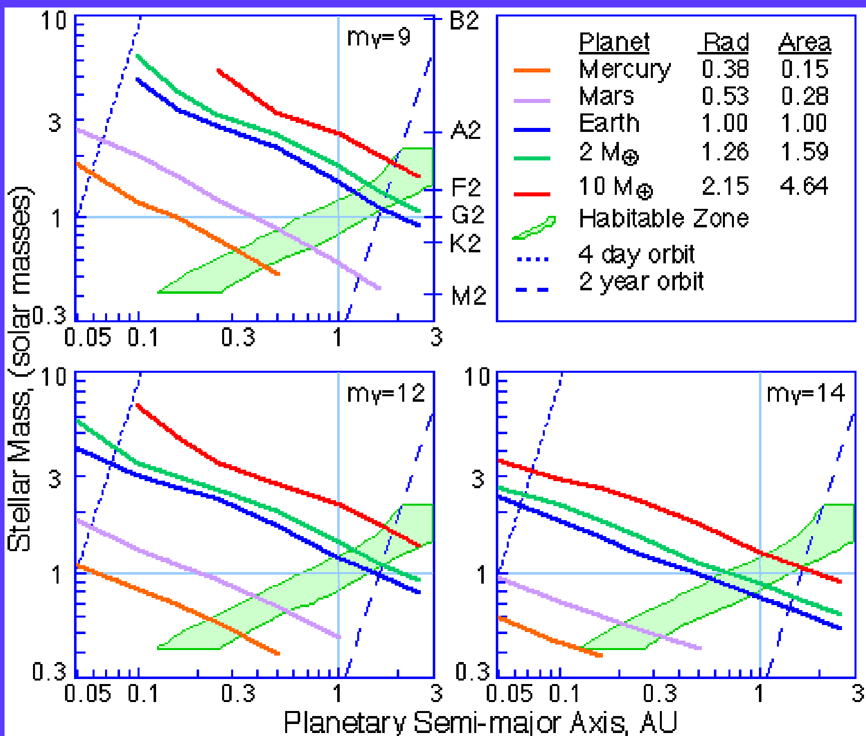
probability that stars with radius R_* have planets with radius R_p and semi-major axis a

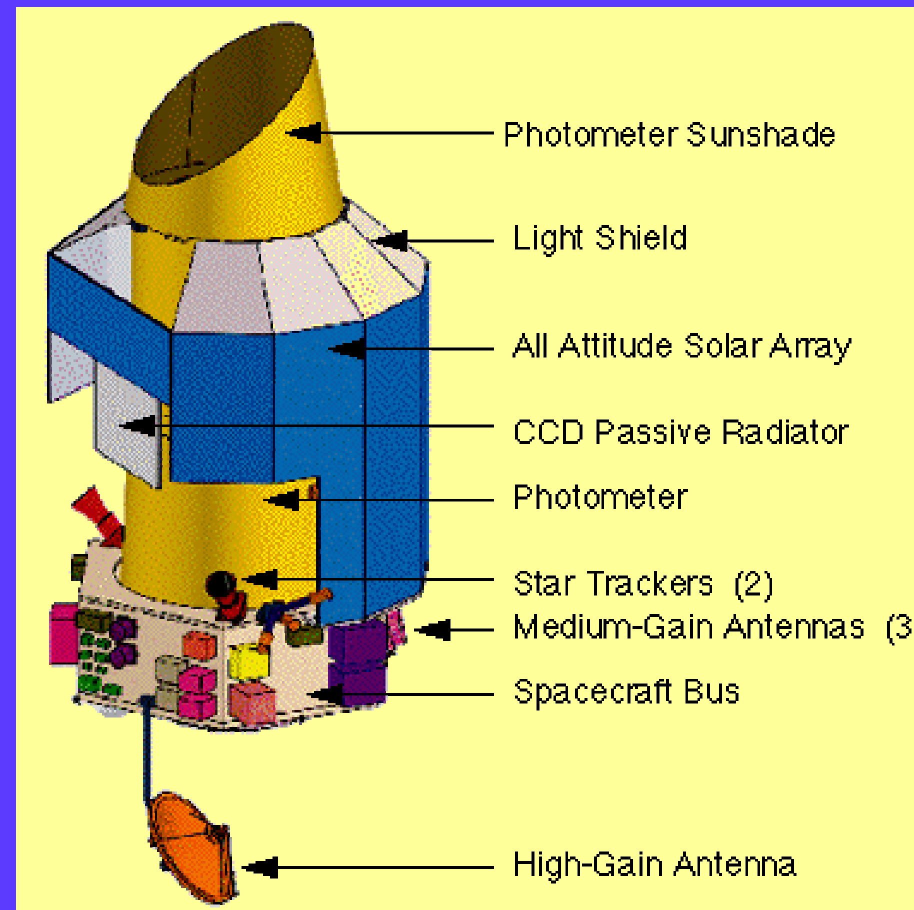
visibility of transit for a system with orbital period T_{orbit}, transit duration t_T, transit depth $dm = 2.5\log(1+R_p^2/R_*^2)$

- **Expect to have ~10 transit candidates by monitoring 10000 stars (per night , most optimistically) !**
  - Photometric follow-up with APO 3.5m
  - Spectroscopic follow-up with Subaru HDS

Kepler (NASA:launch 2005)

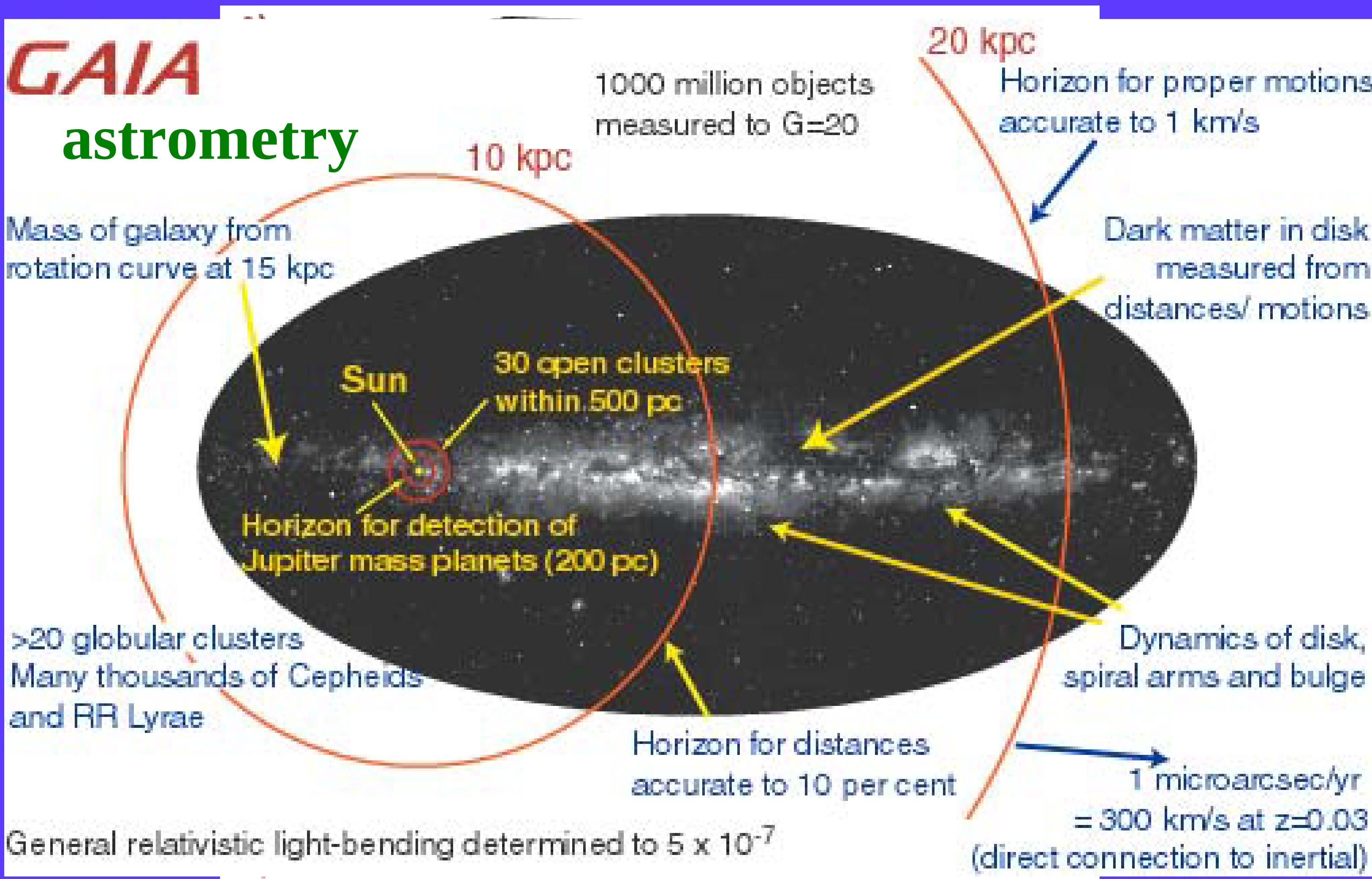
differential photometry





http://www.kepler.arc.nasa.gov/

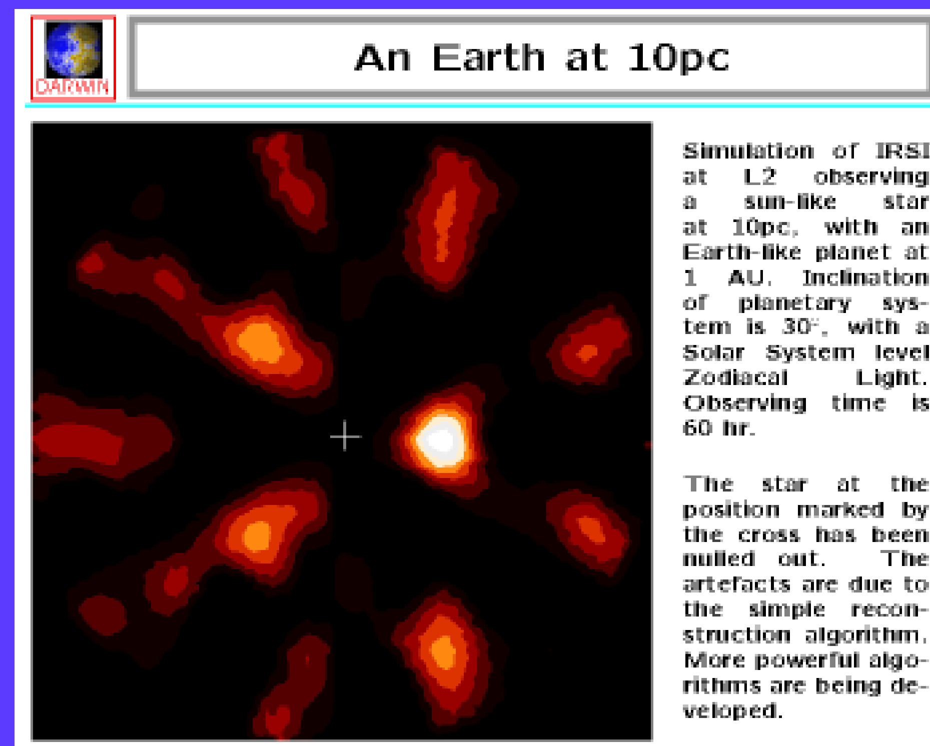
GAIA (ESA: launch 2008-2013)



http://astro.estec.esa.nl/GAIA/

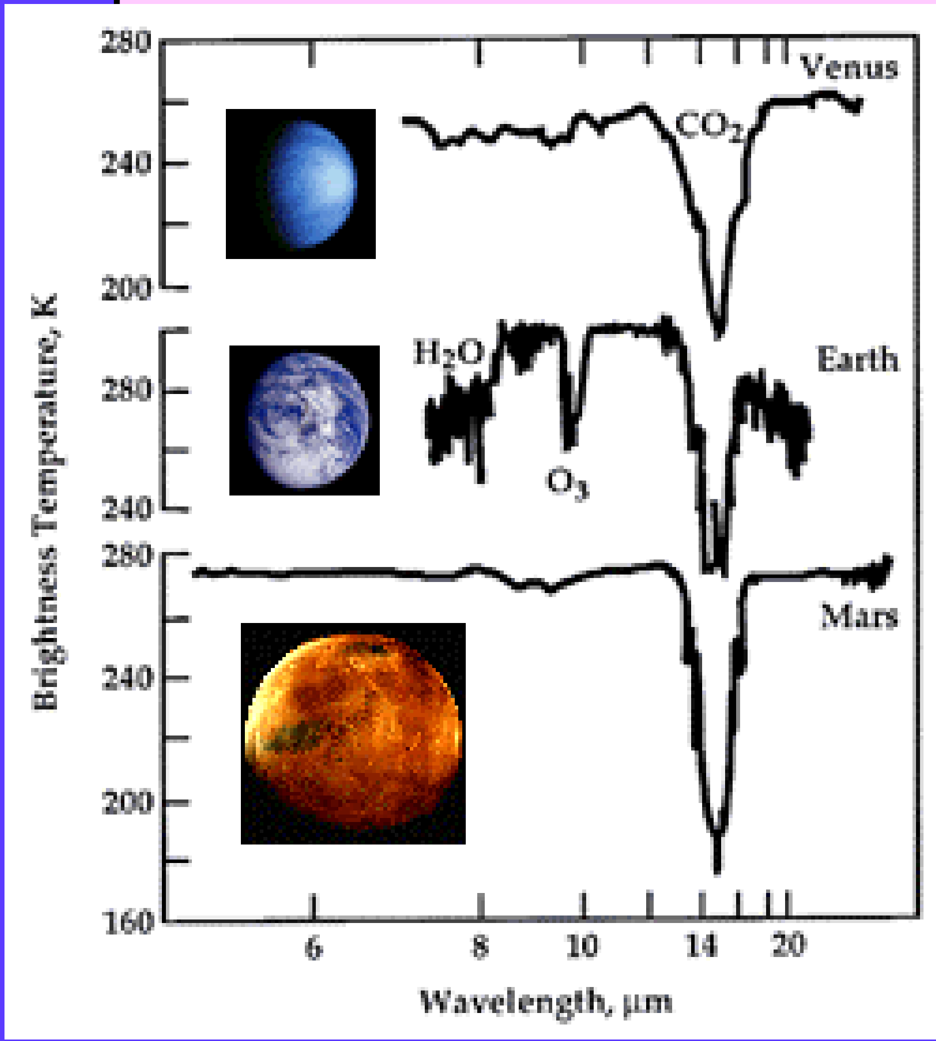
Darwin(ESA:launch after 2015)

infra-red space interferometry: imaging and spectroscopy



http://ast.star.rl.ac.uk/darwin/

Summary and outlook



- Signature of life from the spectroscopic obs.
  - shape of the spectrum
    ⇒ planet's temperature
    ⇒ liquid water ?
  - strong **CO_2** absorption band ⇒ atmosphere ?
  - **O_3** absorption band
    ⇒ abundant oxygen
    ⇒ produced by life ?
  - **H_2O** absorption band
    ⇒ sea in the planet ?

Goal of cosmology in the 21st century

A great Chinese philosopher, Confucius (孔子), was born in 551, B.C. at 中国山東省曲阜.

論語 卷第一 學而第一章 (**http://www.confucius.org/**)

子曰、學而時習之、不亦説乎、有朋自遠方來、不亦樂乎、人不知 慍、不亦君子乎。

공자께서 말씀하셨다.

"배우고, 때때로 익히니 즐겁지 ? 먼곳에서 찾아와줄 친구'가 있으니 행복하지 아니하나? 남들이 알아주지 않아도 괘념치 않으니 이것이 군자다움이 아니겠느냐?"