Searching for the atmospheric signature of transiting extrasolar planets

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12:00 July 23, 2004, Planetary science seminar
University College London

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 ?***

P. Ulmschenider: "Intelligent Life in the Universe" (Springer 2003)

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

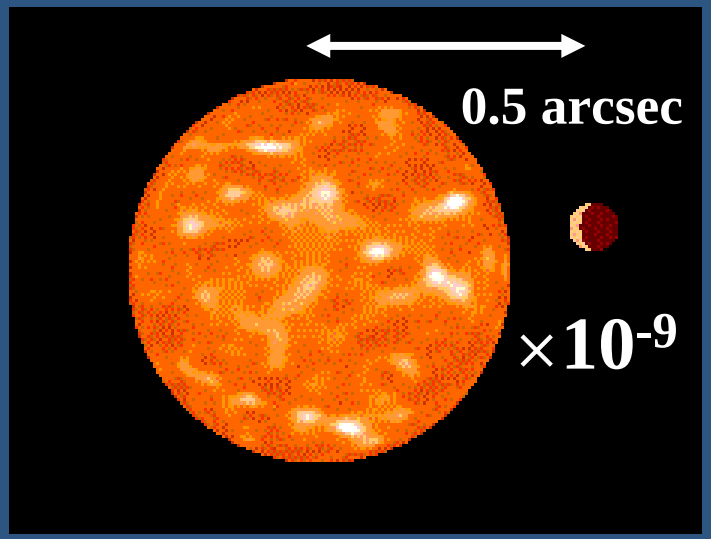
Why extrasolar planets ***now*** ?

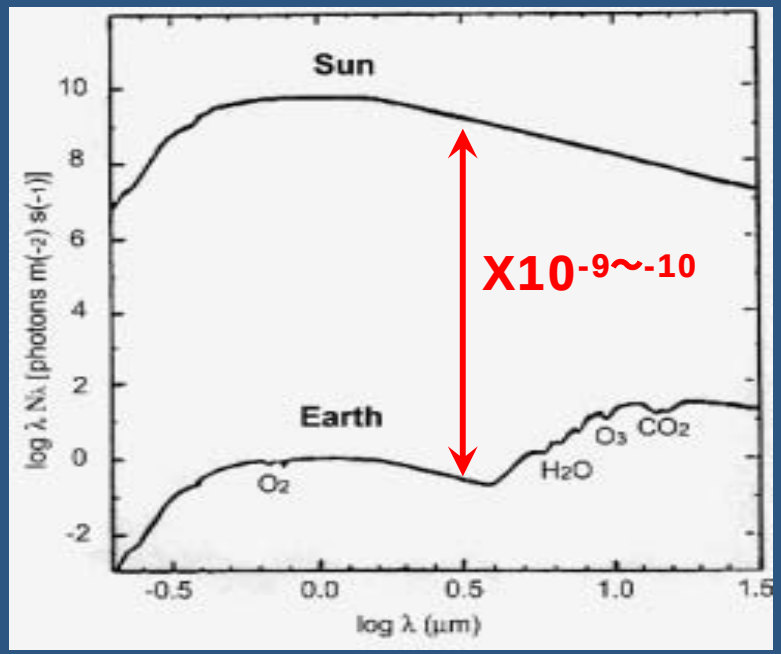
- **directly related to one of the most fundamental questions**
  - origin of life
- **Just started**
  - first discovery in 1995 !
- **easier to convince taxpayers**
  - other sciences became too detailed or too matured to achieve really fundamental contribution
- **Very few experts in this field, and quite interdisciplinary**
  - whatever experts in physics, planetary science, astronomy, geology, climate, and biology are welcome to join in many respects

Direct imaging ?

Jupiter at a distance of 10 pc

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

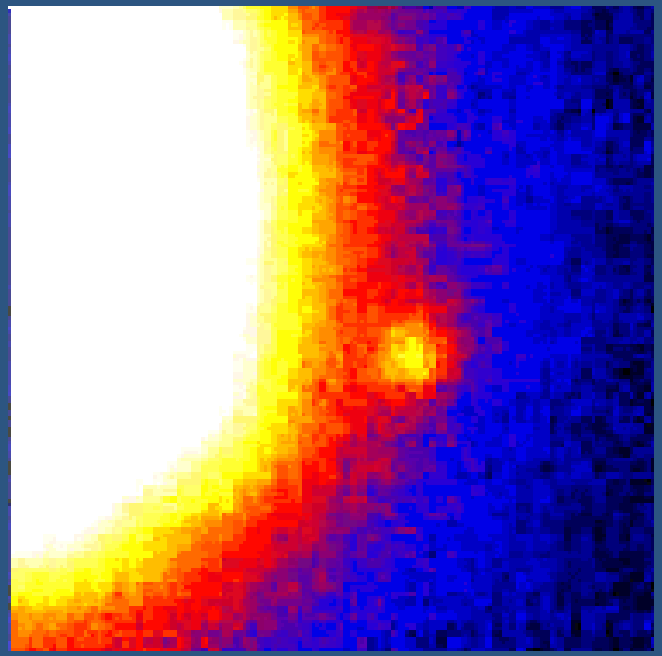


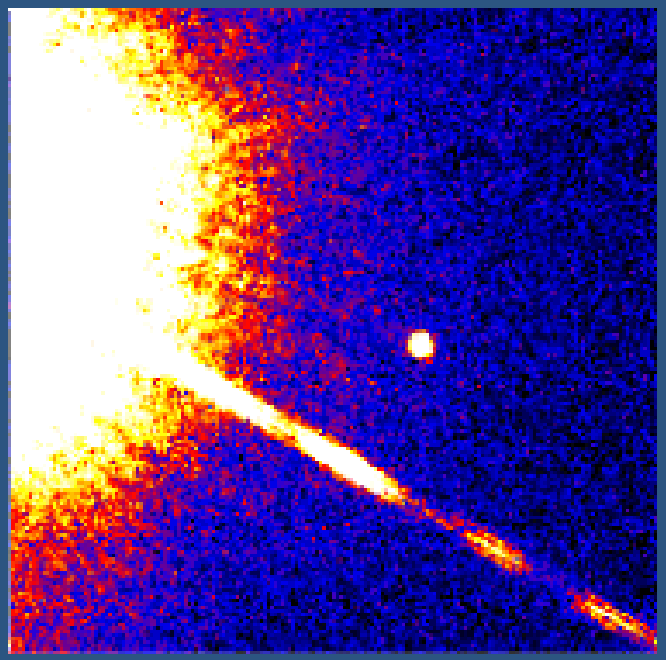


need to detect a 10^{-9} times darker object than the main star which locates within a typical seeing scale of the ground observation !

⇒ Just impossible !

An *observed* brown dwarf: Gliese 229b



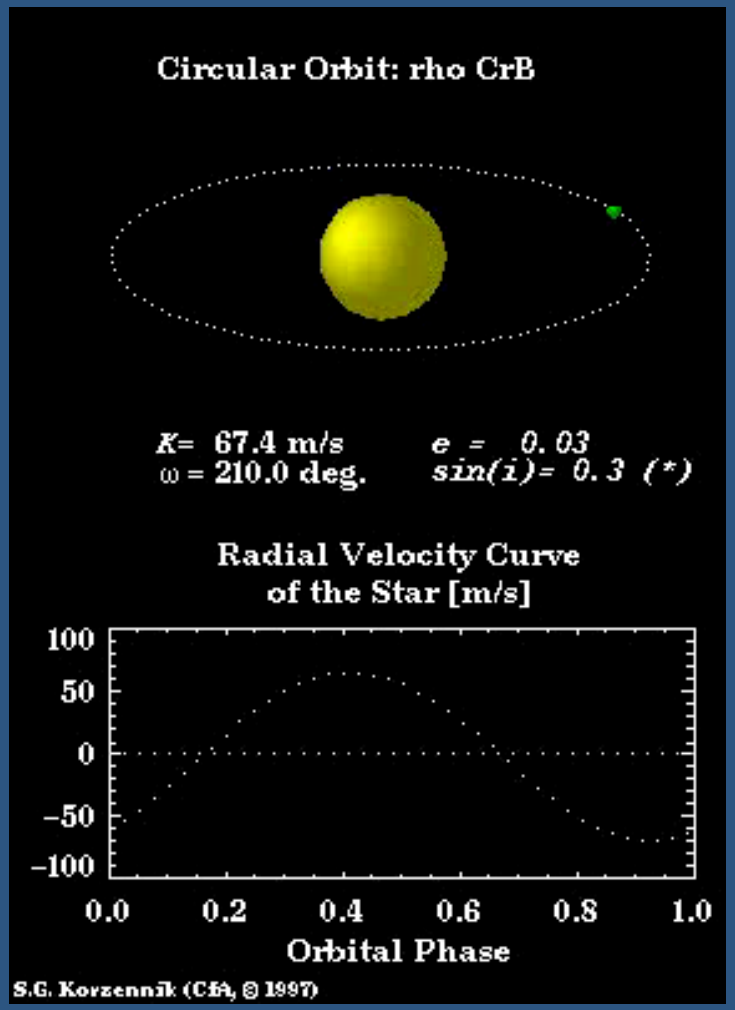


Gliese229 b:
angular separation
7 arcsec
luminosity ratio
5000
left：Palomar
right：HST
(T.Nakajima)

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

Radial velocity of a star perturbed by a planet

Even if a planet is not directly observable, its presence can be inferred dynamically



velocity modulation of the Sun:

12.5 m/s (Jupiter)

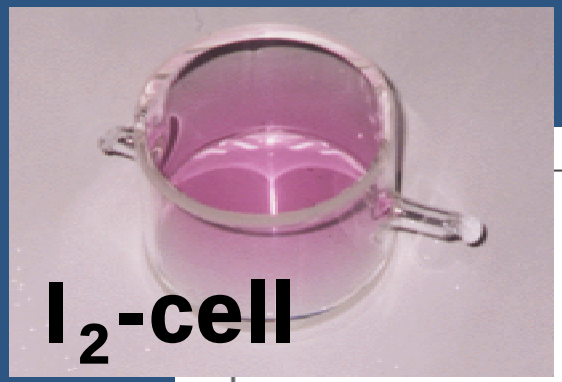
0.1 m/s (Earth)

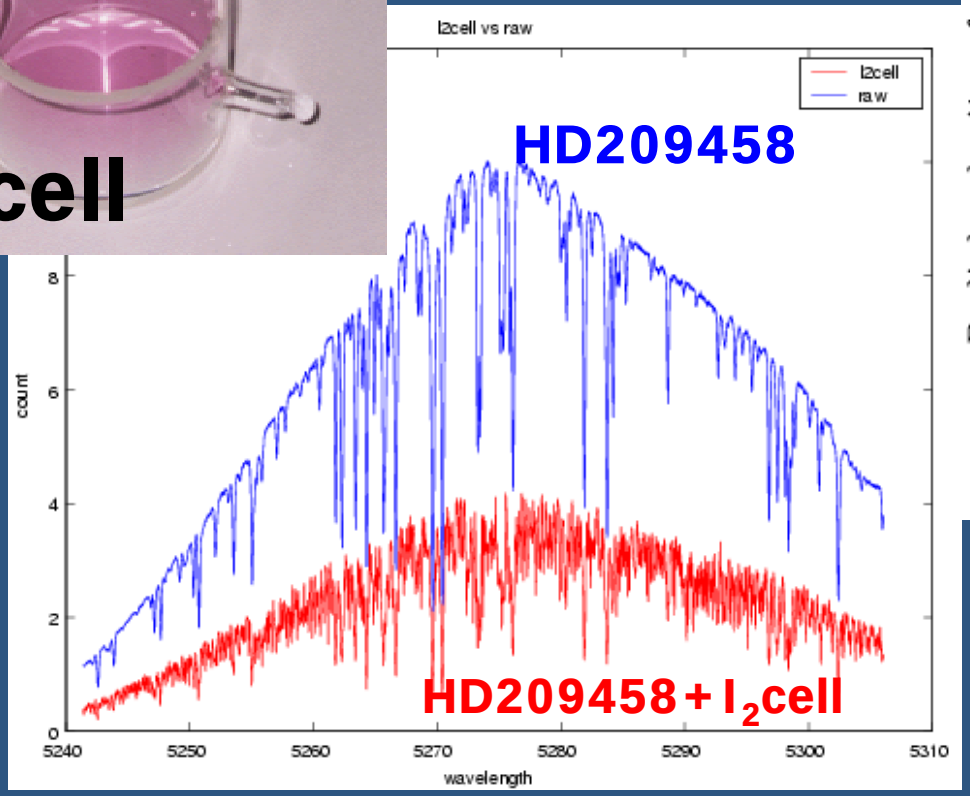
an accuracy of 3m/s achieved from the ground observation

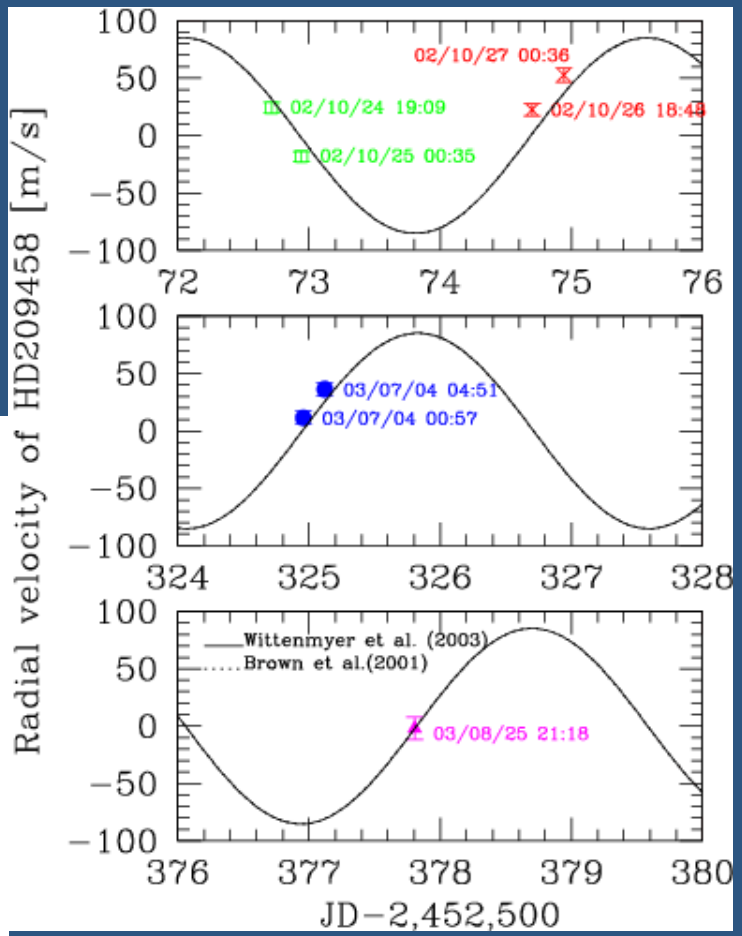
⇒ the current major method in search for Jupiter-sized planets

radial velocity measurement with I_2-cell

- Absorption lines of I_2 as accurate standard rulers
- Accuracy ~3m/s achieved



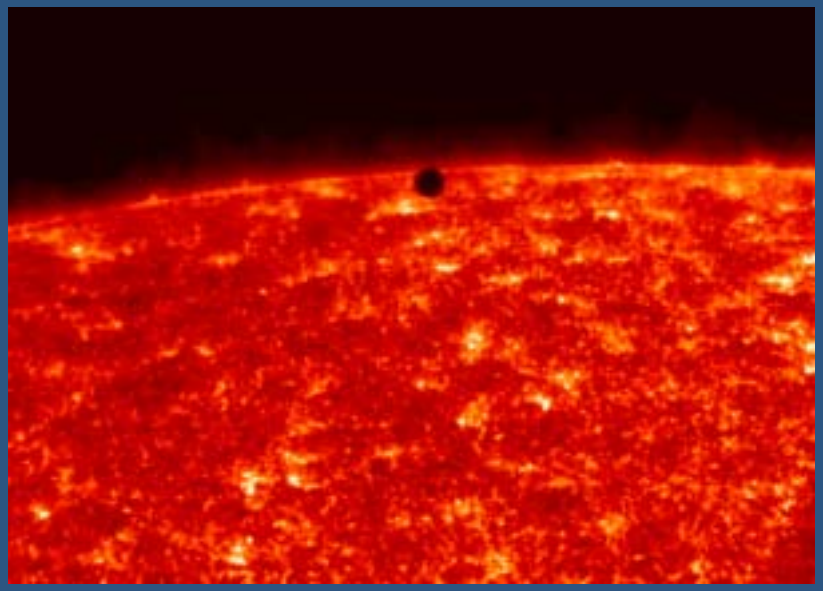




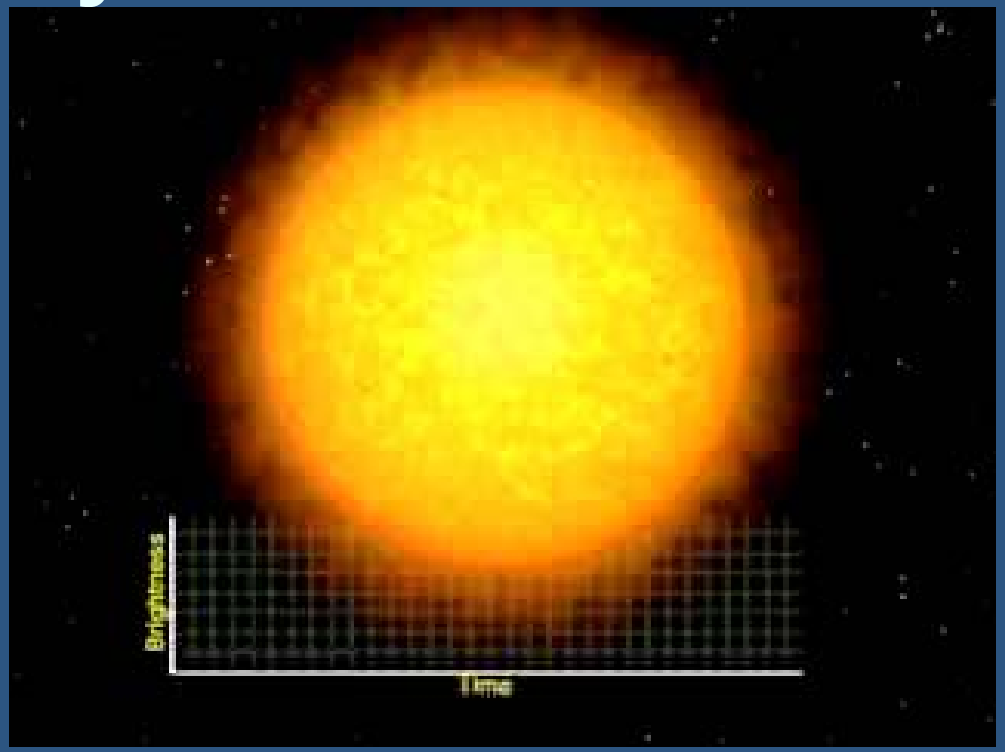
HDS on Subaru

Winn et al. (2004)

Stellar light curve variation due to planetary transit



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



http://hubblesite.org/newscenter/archive/2001/38/

Transit probability: 10% $(0.05\mathrm{AU}/a_{orbit})(R_{star}/R_{Sun})$

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

from the ground: ~ 0.1%; OK for Jupiter, but not for Earth

Transit method for the extrasolar planet search

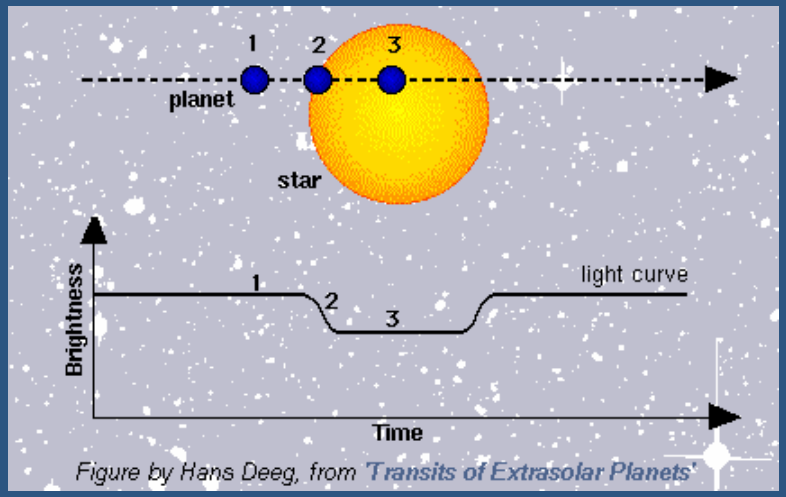


Figure by Hans Deeg, from 'Transits of Extrasolar Planets'

- Precise mass since inclination angle is determined (only observable for edge-on system: *inclination* ~ 90 deg.)
- size of the planet can be estimated
- complementary to the radial velocity method
- Low probability:

$$10\% \ (0.05\mathrm{AU}/a_{orbit})(R_{star}/R_{Sun})$$

- Small flux variation:

$$1\% (R_{planet}/R_{Jupiter})^2 (R_{Sun}/R_{star})^2$$

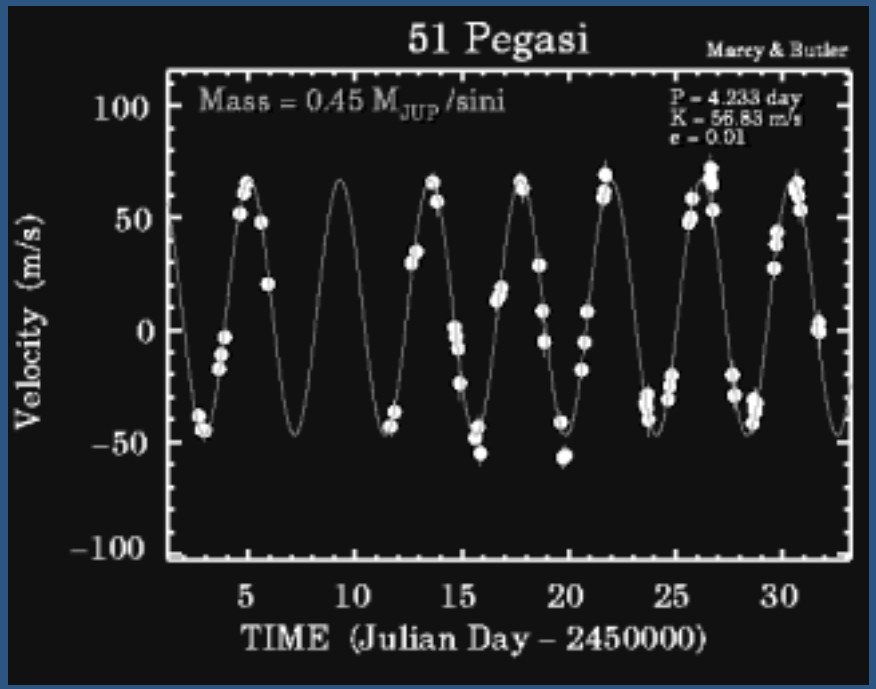
A brief history of the discovery of extrasolar planets

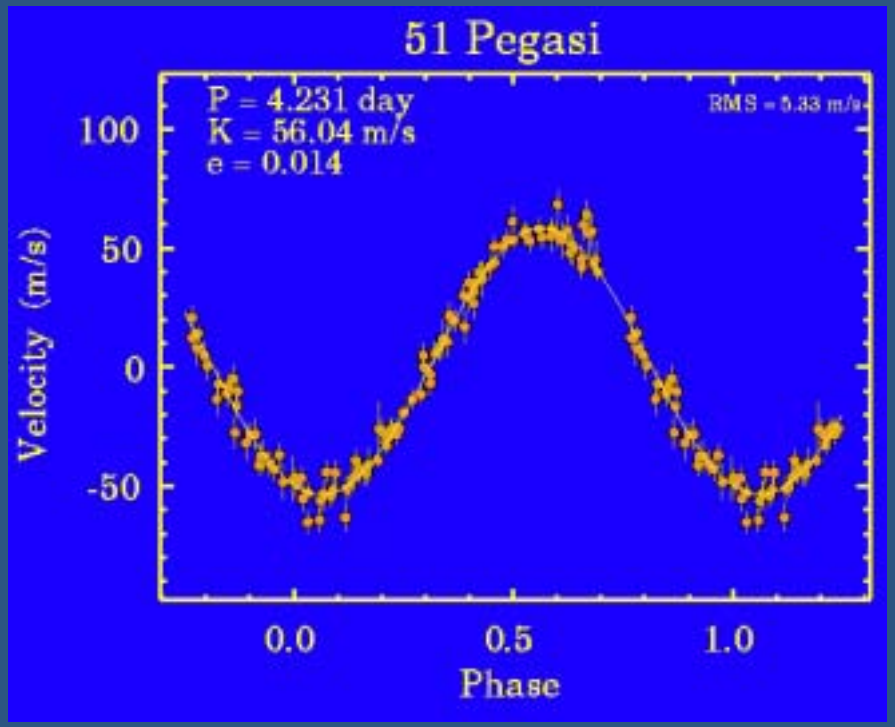
- ***1995*:** the first extrasolar planet around the main sequence star 51 Pegasi (Mayor & Quelos)
- ***1999*:** transit of a known planet around HD209458 (Charbonneau et al., Henry et al.)
- ***2001*:** discovery of Na in the atmosphere of HD209458b
- **2003:** first discovery of a planet by transit method *alone* (1.2 day orbital period: OGLE)
- *123 extrasolar planets* are reported (July 8, 2004)

http://exoplanets.org/

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

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

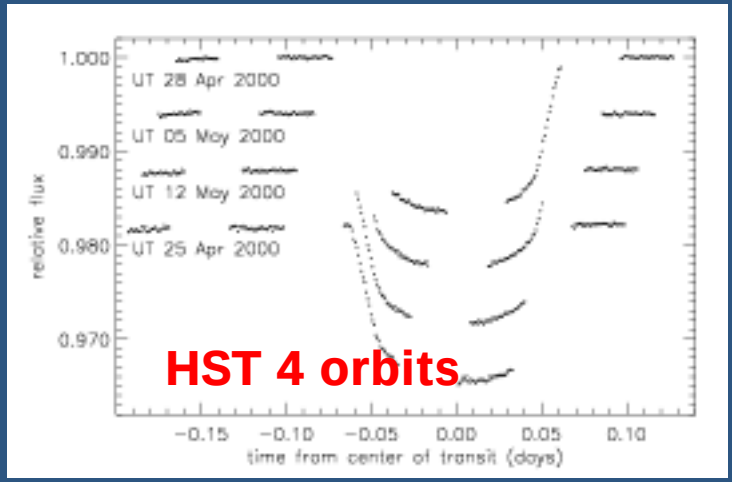


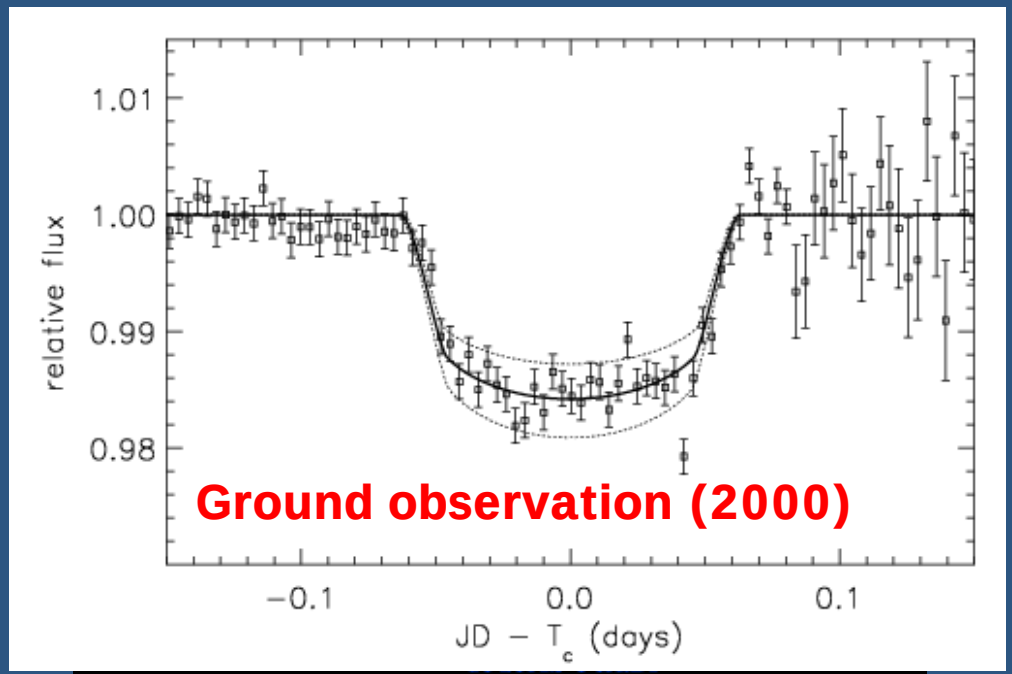


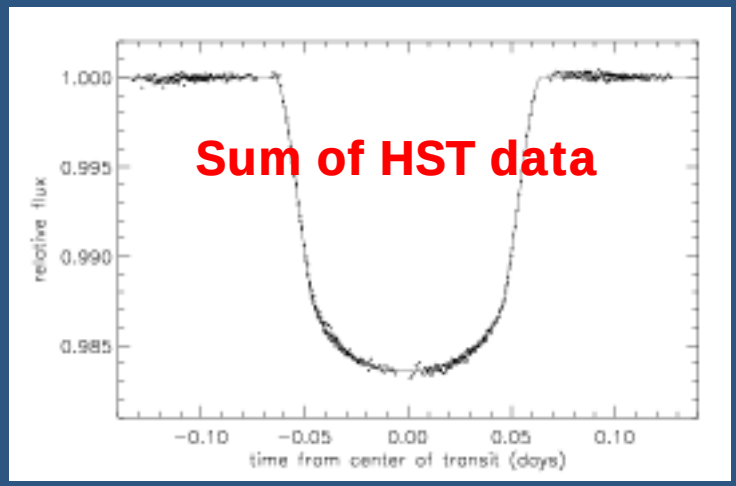
<u>P=4.2 days !</u>

the first discovery of the transit of a planet: HD209458

- detected the light curve change at the phase consistent with the radial velocity (Charbonneau et al. 2000, Henry et al. 2000)







Brown et al. (2001)

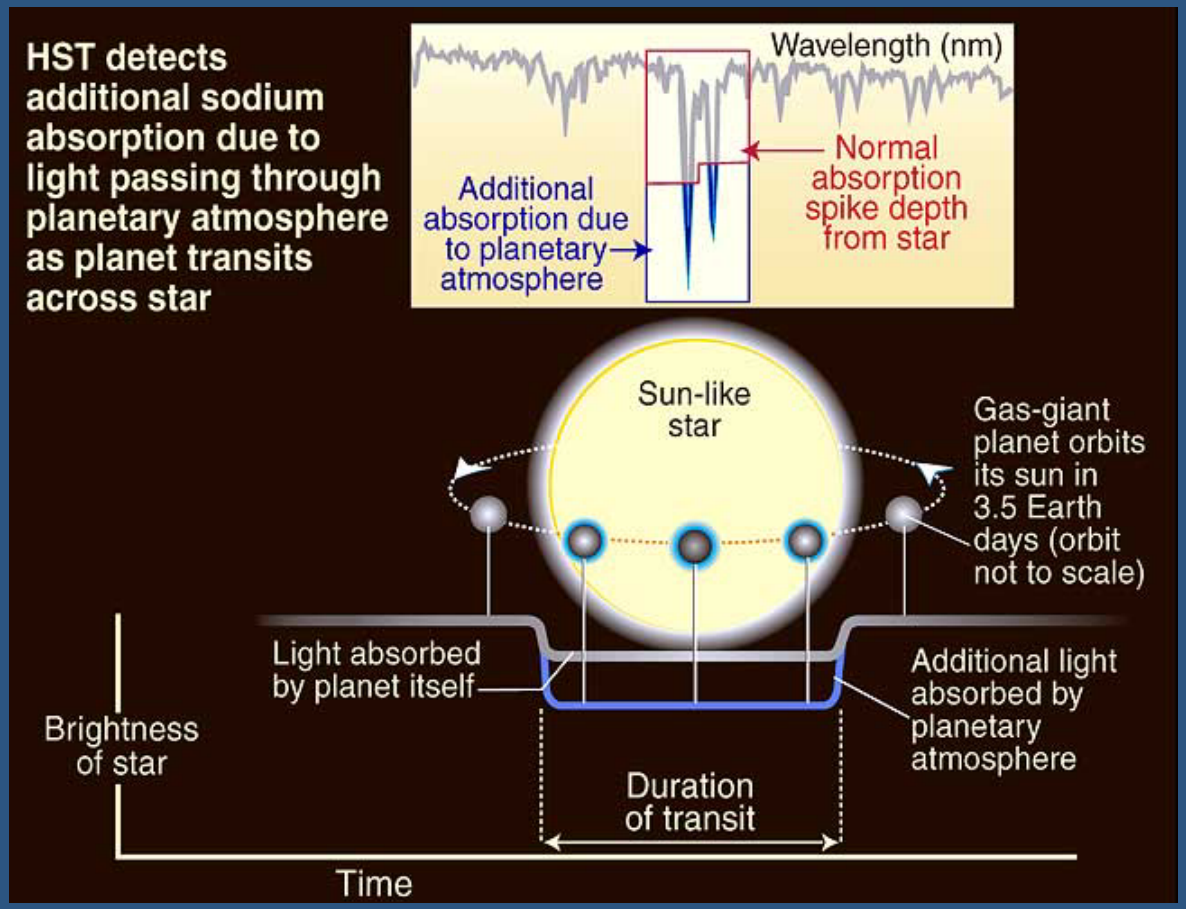
Estimated parameters of HD209458b

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 $R_{Jupiter}$**

- First ever convincing evidence for the case of an extrasolar planet !
- M_p=0.63 M_J, R_p=1.3 R_J
- ρ =0.4 g/cm^3 < Saturn's density
- Gas planet ! (not black hole, rock …)
- g=970 cm/s^2

First detection of atmospheric absorption of HD209458b with HST

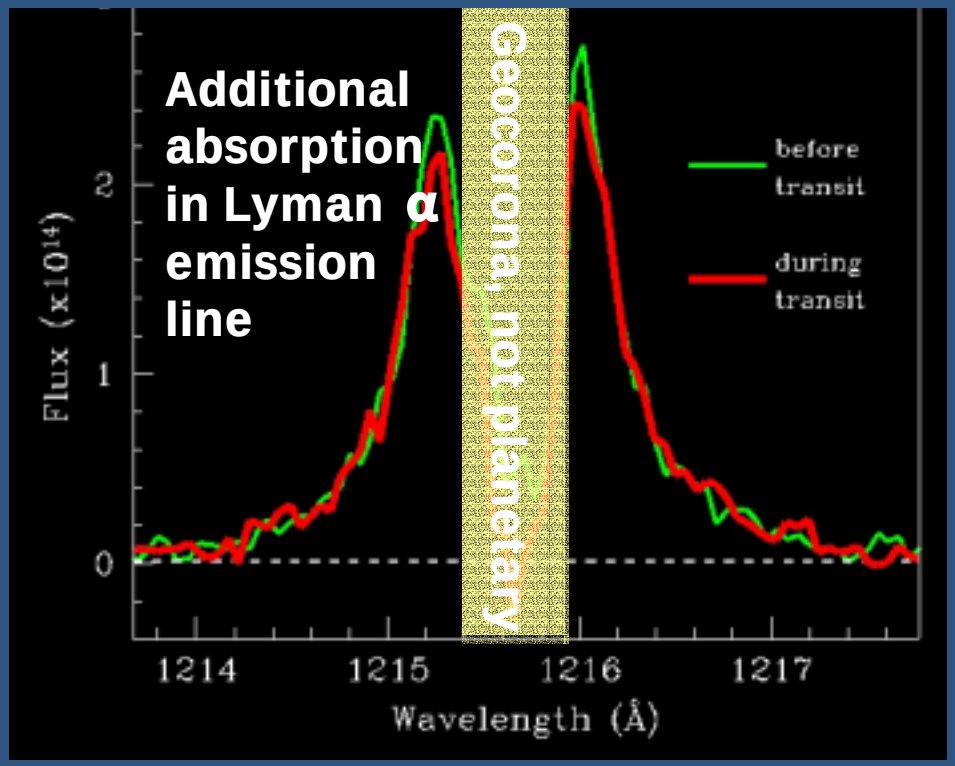
http://hubblesite.org/newscenter/archive/2001/38/



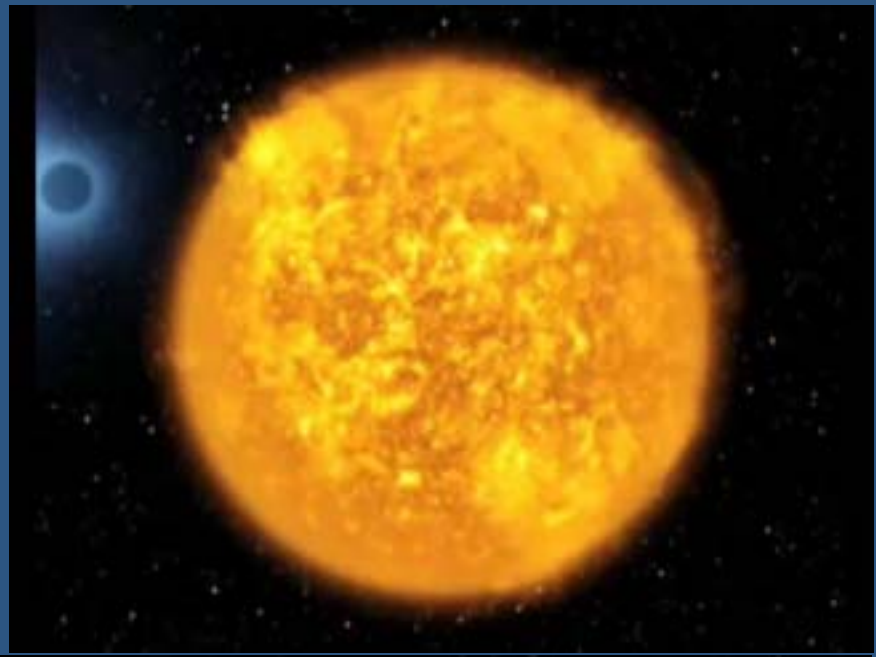
- **Nov. 2001: additional sodium absorption during the transiting phase (Charbonneau et al. 2002)**
- **The first detection of atmosphere of an extrasolar planet**

HD209458b : evaporating planet ?

Unexpectedly large amount of
Ly α absorption (15%)
⇒ evaporating neutral hydrogen cloud ?



Vidal-Madjar et al. Nature 422(2003)143



http://hubblesite.org/newscenter/archive/2003/08/

Subaru observation

“Spectro-photometric search for scattered light from HD209458b”

S02B-16 on October 24 and 26, 2002

Yasushi Suto, Norio Narita (Univ. of Tokyo)

Toru Yamada, Wako Aoki (National Ast. Obs. Japan)

Bun-ei Sato (Kobe Univ.)

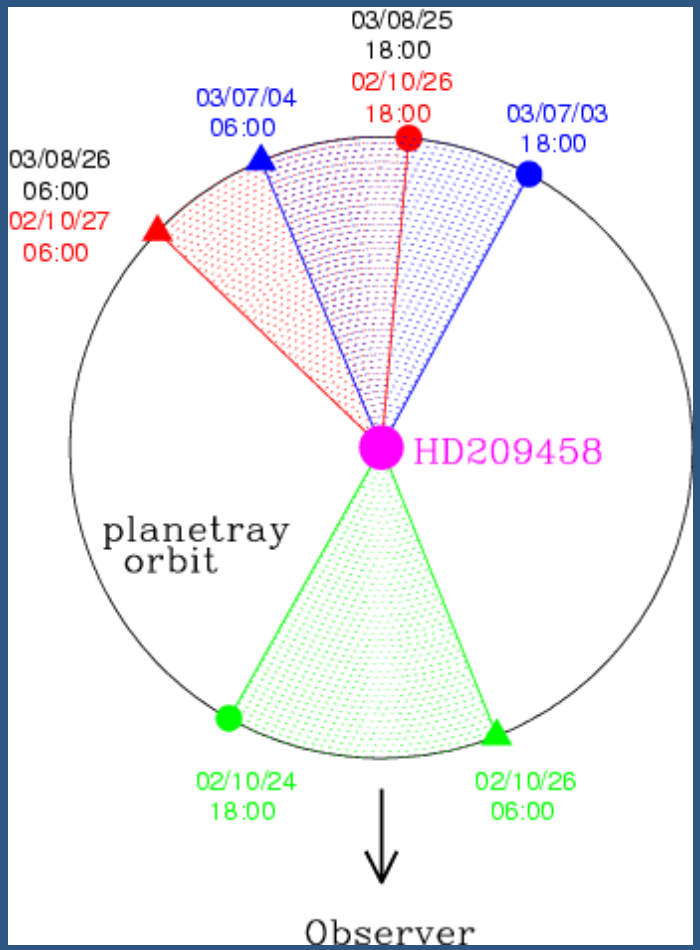
Edwin L. Turner , Brenda Frye (Princeton Univ.)

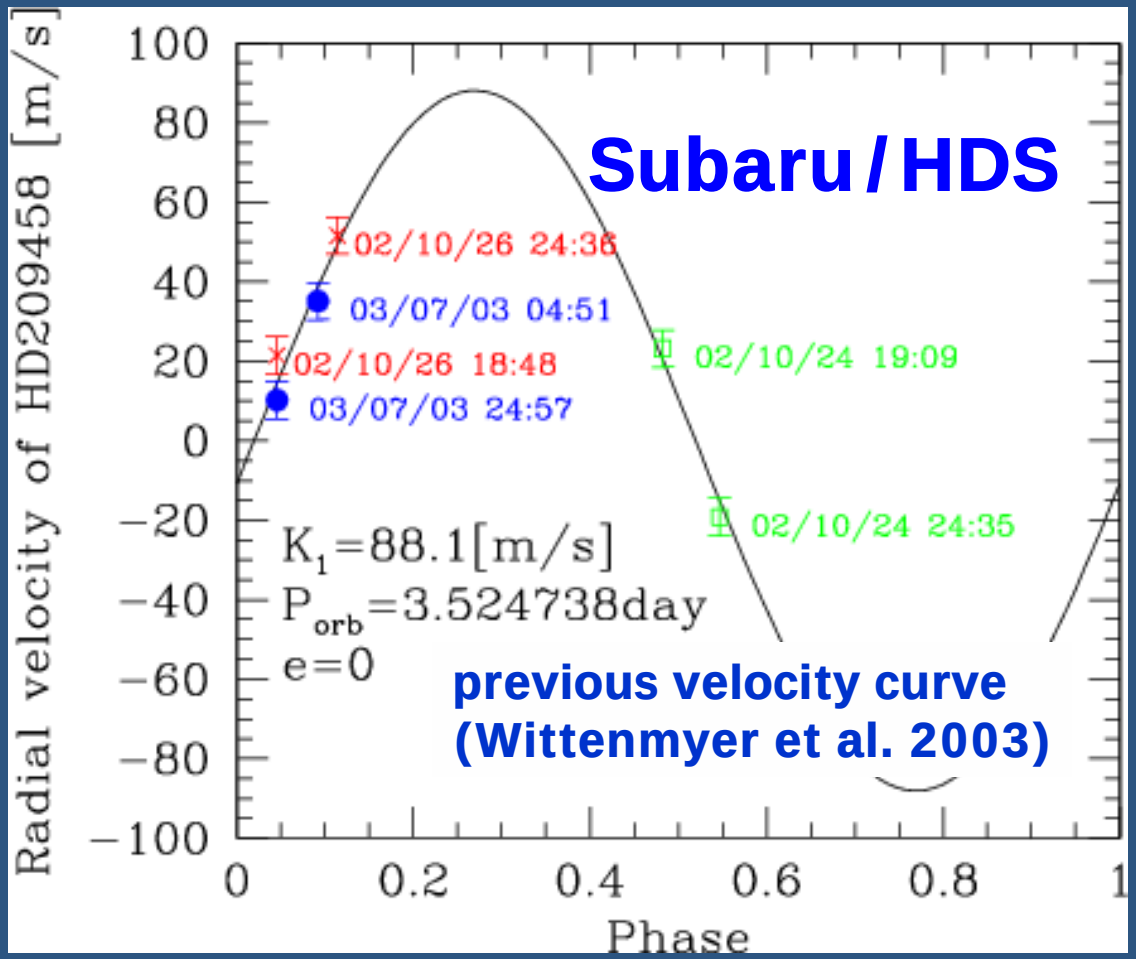
Josh Winn (Harvard Univ.)

On-going three projects with HDS

- **Search for the planetary atmosphere from the ground observation**
  - Hα absorption analysis completed; upper limit $\sim$0.1%
  - Winn et al. (2004) PASJ, in press (astro-ph/0404469)
  - Analysis of other lines in progress (Narita et al. 2004)
- **Constraining the stellar spin and the planetary orbital axes from the Rossiter-McLaughlin effect**
  - New analytic formulae (Ohta, Taruya & Suto 2004)
  - Analysis in preparation (Narita et al. 2004)
- **Search for reflected light from planets**
  - Just started collaboration with a group in UK !
  - St. Andrews University (A. Cameron, C. Leigh)

Orbital phase and radial velocity of HD209458b in our observing run





Winn et al. (2004) PASJ, in press. astro-ph/0404469

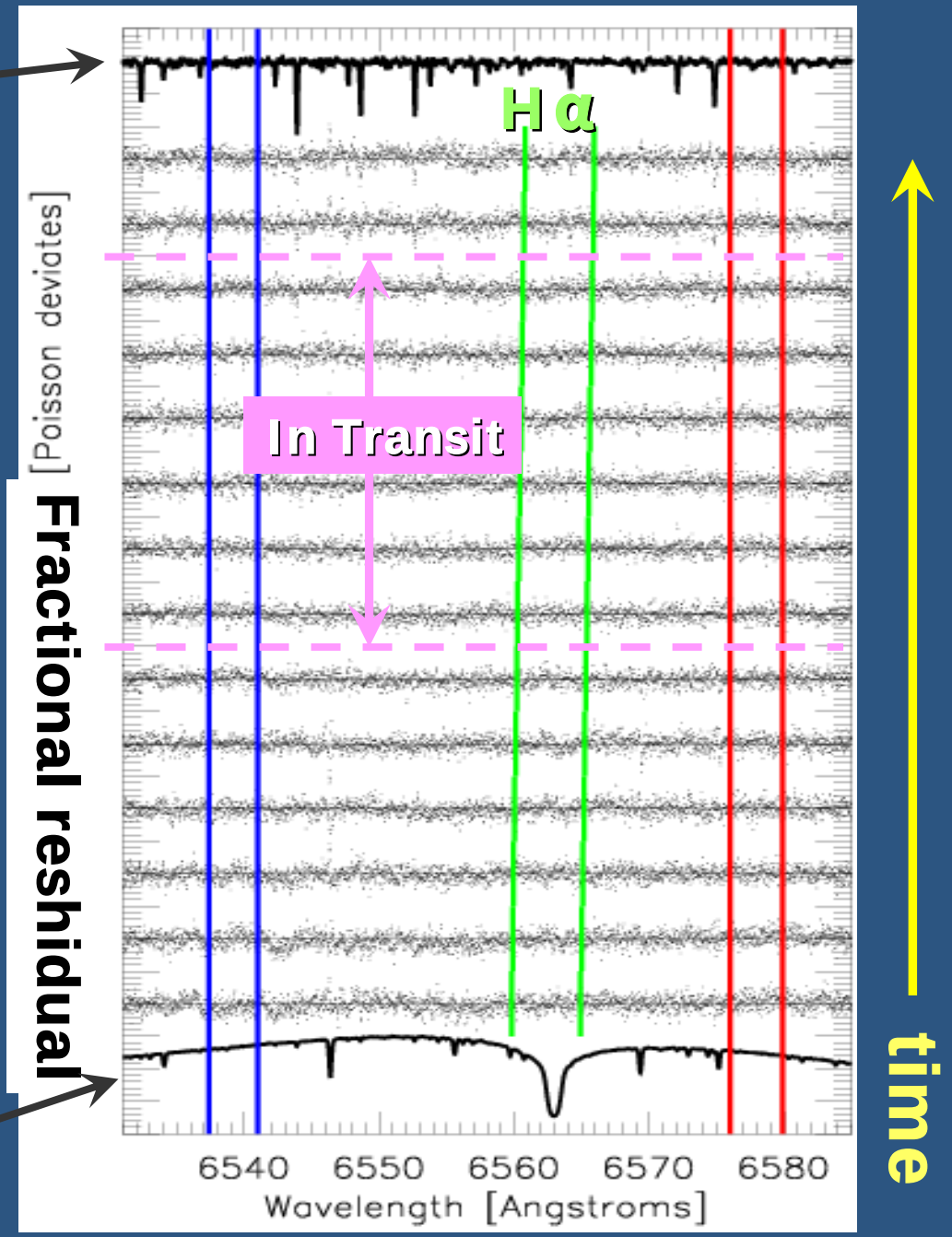
Telluric spectrum

search for Hα absorption due to the atmosphere of HD209458b

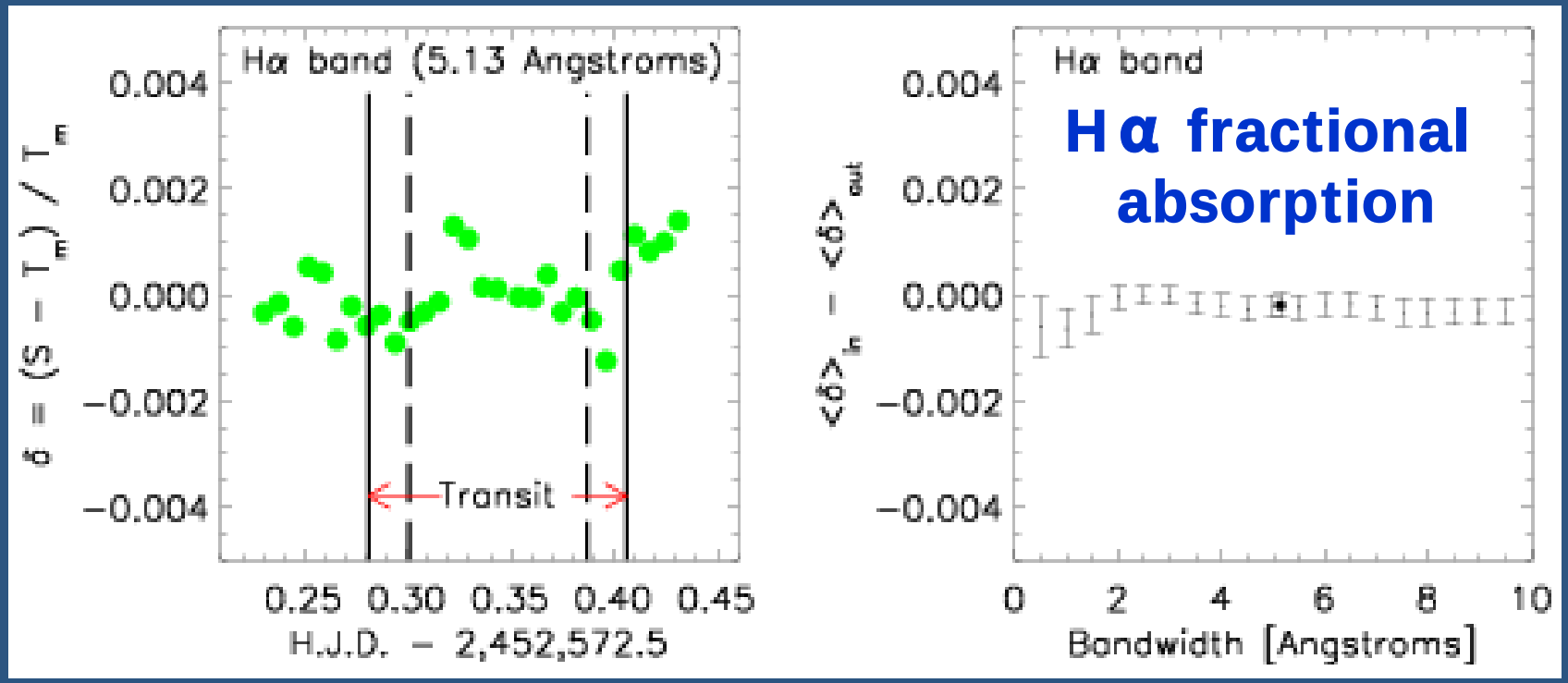
Na I (D2)	5889.97 Å
Na I (D1)	5895.94 Å
Hα	6562.81 Å
Hβ	4861.34 Å
Hγ	4340.48 Å

Template steller spectrum

Winn et al. (2004)



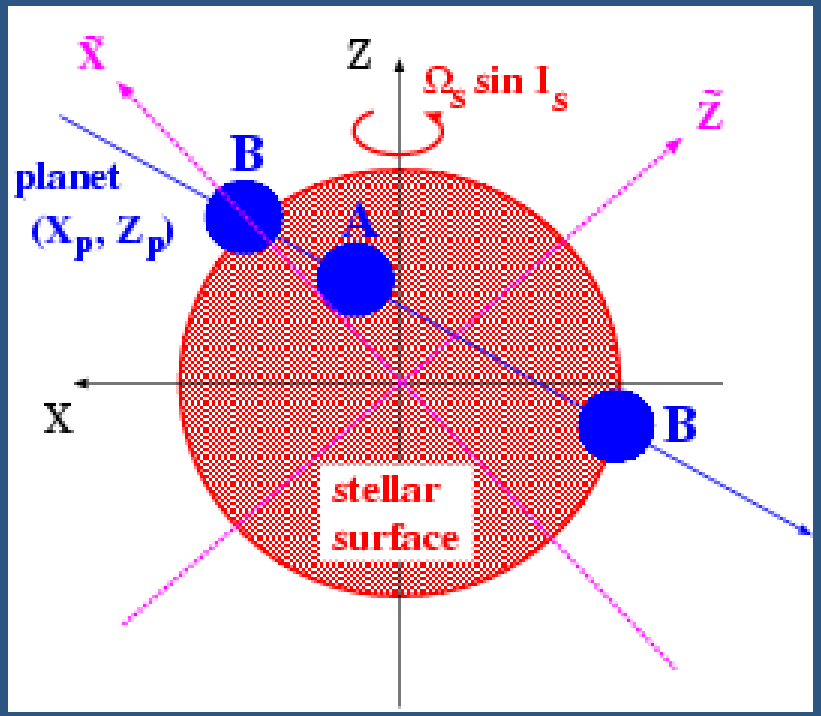
The most stringent upper limit on the Hα absorption in the atmosphere of HD209458b



- Hα absorption <0.1% (Winn et al. 2004)
- Ly α absorption=15% (Vidal-Madjar et al. 2003)
  - $T_{excitation}$< (0.6-1.3)eV (***heavily*** model-dependent)

The Rossiter-McLaughlin effect

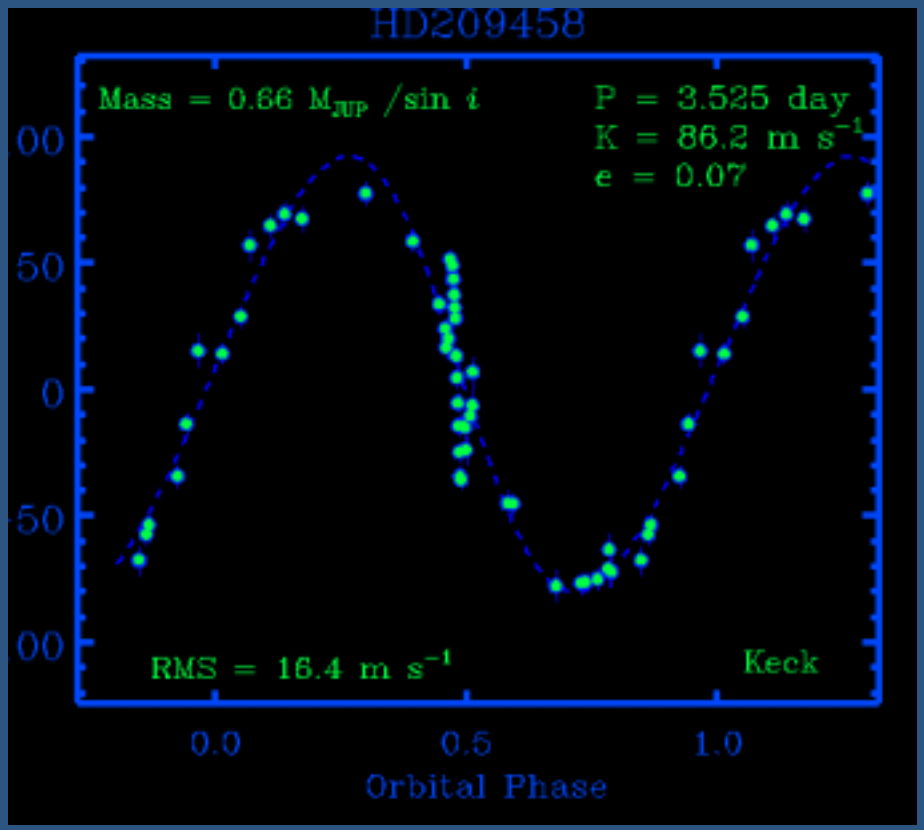
During a transit of a planet, flux from a part of stellar surface is blocked which induces a time-dependent asymmetry in the stellar Doppler broadened line profile. This produces an apparent anomaly of the stellar radial velocity.

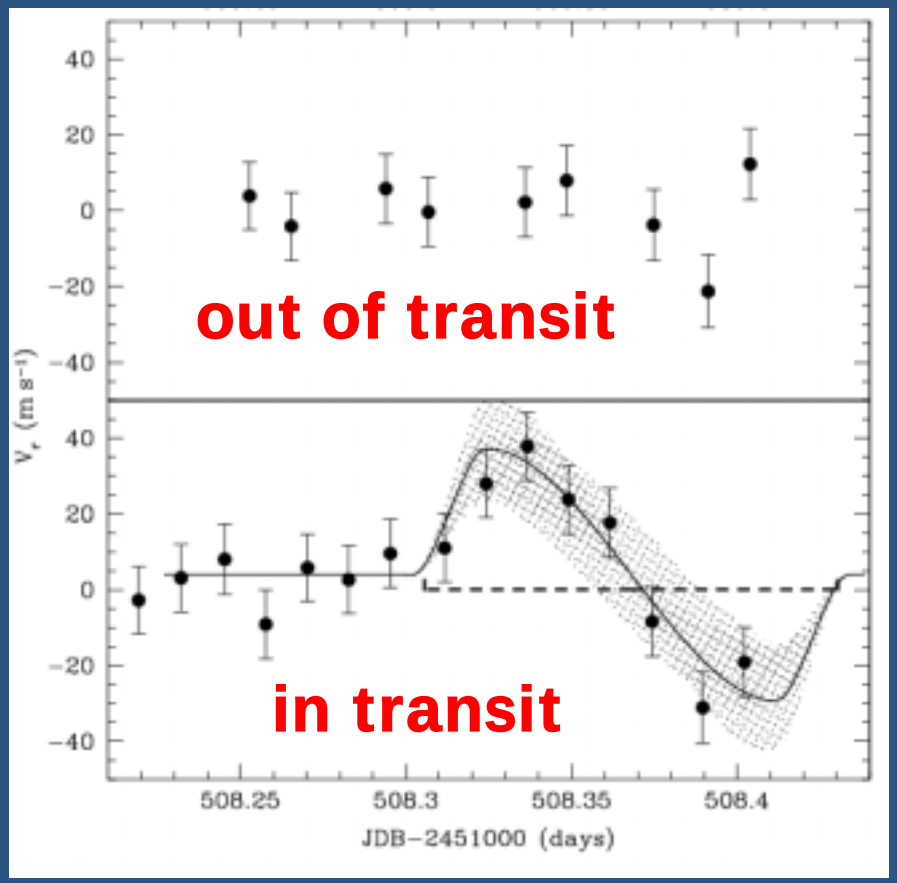


originally discussed in eclipsing binary systems (Rossiter 1924; McLaughlin 1924)

Spectroscopic transit signature: the Rossiter-McLaughlin effect

Origin of angular momentum

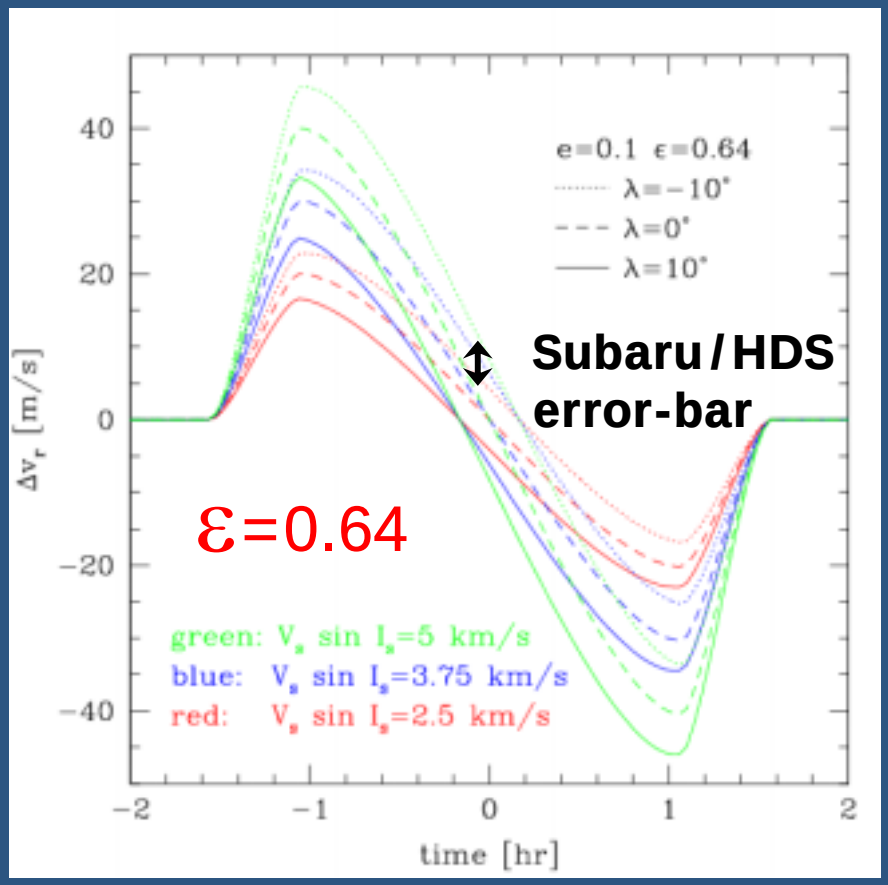


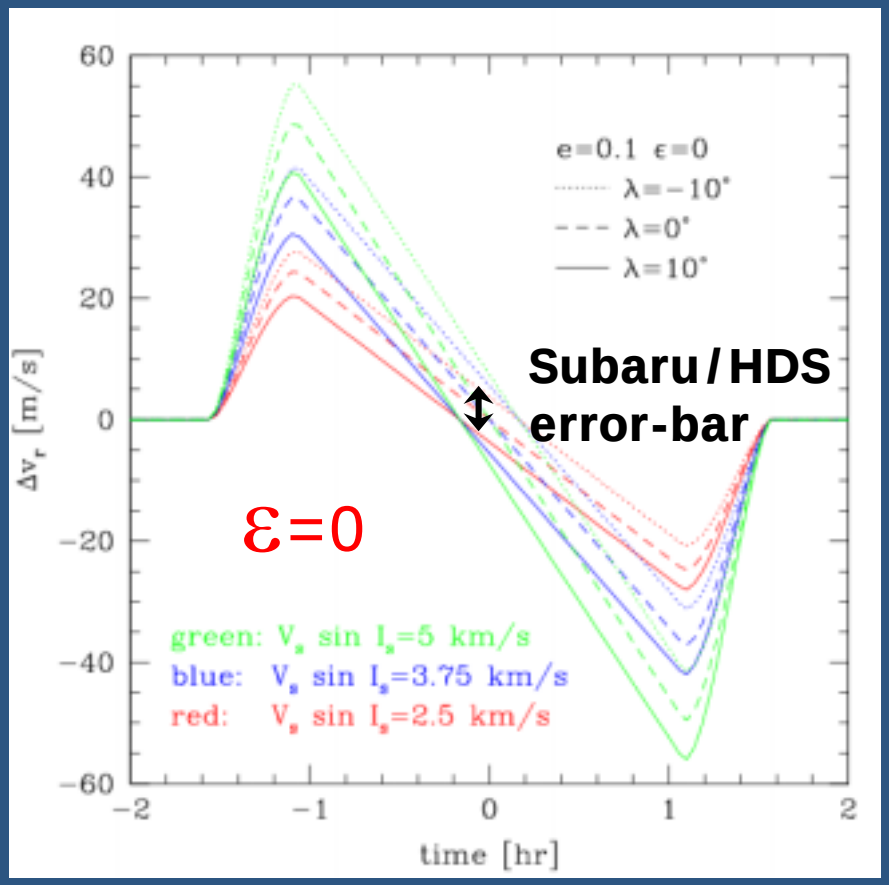


HD209458 radial velocity data
http://exoplanets.org/

Stellar rotation and planetary orbit
Queloz et al. (2000) A&A 359, L13
ELODIE on 193cm telescope

Analytic templates for the velocity anomaly due to the Rossiter -McLaughlin effect

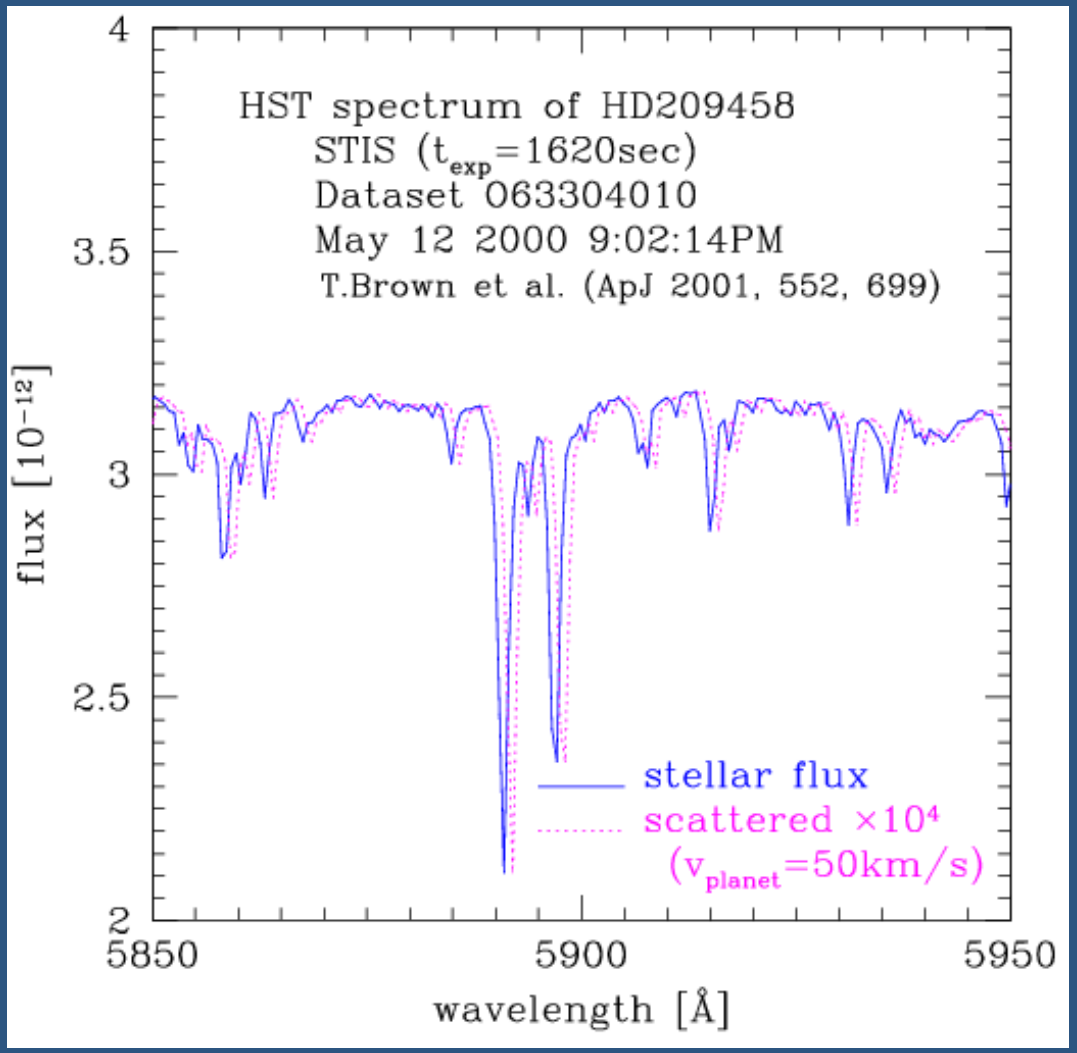




Limb darkening: $B = 1 - \varepsilon\,(1 - \cos\theta)$

(Semi)-analytic template curves (Ohta, Taruya & Suto 2004)

Search for scattered light from HD209458b



- Statistical search for the scattered components Doppler-shifted at $v_p(t)$ from the stellar absorption lines.
- The spectral resolution of HDS ($\lambda/\Delta\lambda$=50000) is 10 times better than that of STIS, HST ($\lambda/\Delta\lambda$=5540).

A possible roadmap of sciences of extrasolar planet

- Discovery phase of gas giant planets
- Discovery phase of planetary atmosphere
- Detailed spectroscopic study of planets
- Discovery of terrestrial planets
- ***Identifying Biomarker***
  - Red-edge of extrasolar plant ?
- ***Discovery of Habitable planet***
- ***Discovery of Extraterrestrial life***

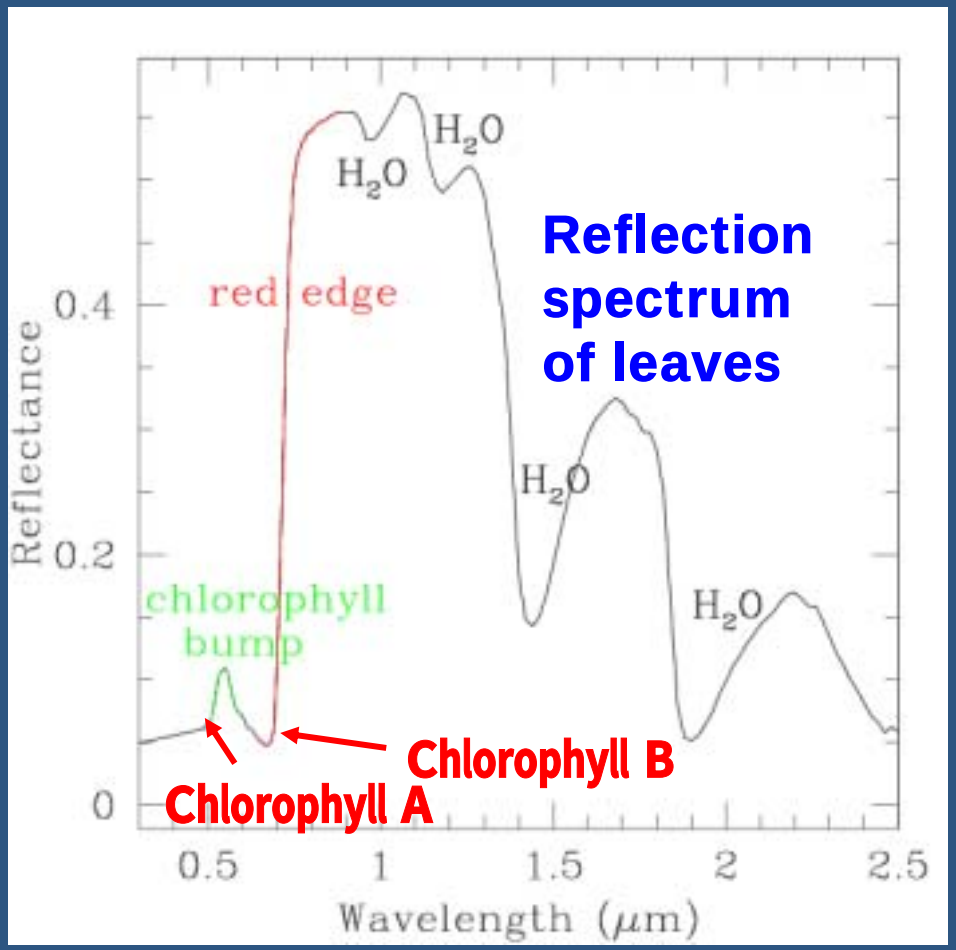
Astrobiology ? Not yet

- Discovery of extrasolar planets is a wonderful breakthrough in astronomy (and philosophy, maybe)
- But mere discovery has no biological information
- **How can we identify the signature of life ?**
  - **Biomarker**
- Suppose our earth is located at 10pc away. Can we identify any signature of life from photometric and spectroscopic data alone ?
  - **Earth-shine**

http://modarch.gsfc.nasa.gov/
http://www.nasa.gov/home/index.html

Red edge of *(extrasolar) plants:* a biomarker in *extrasolar planets*

- Significant reflectivity of leaves of terrestrial planets for $\lambda > 7000$ Å
- An interesting (maybe unique) candidate for a biomarker ?
- ***extrasolar plants*** as a biomarker in *extrasolar planets*



Seager, Ford & Turner
astro-ph/0210277

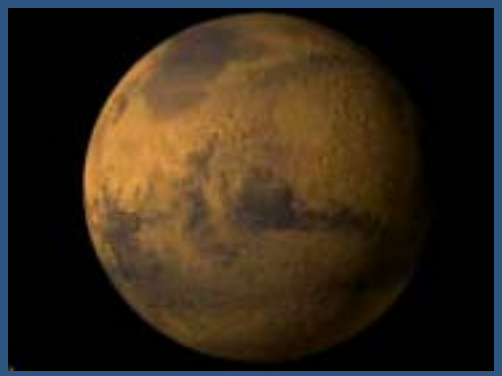
Vesto Melvin Slipher (1875-1969)

Red-edge as a biomarker (at least) in 1924 !

- Discovered redshifts of “spiral nebulae” now known as galaxies
- Essential contribution for Hubble’s discovery of expanding universe

“Observations of Mars in 1924 made at the Lowell Observatory: II spectrum observations of Mars’’

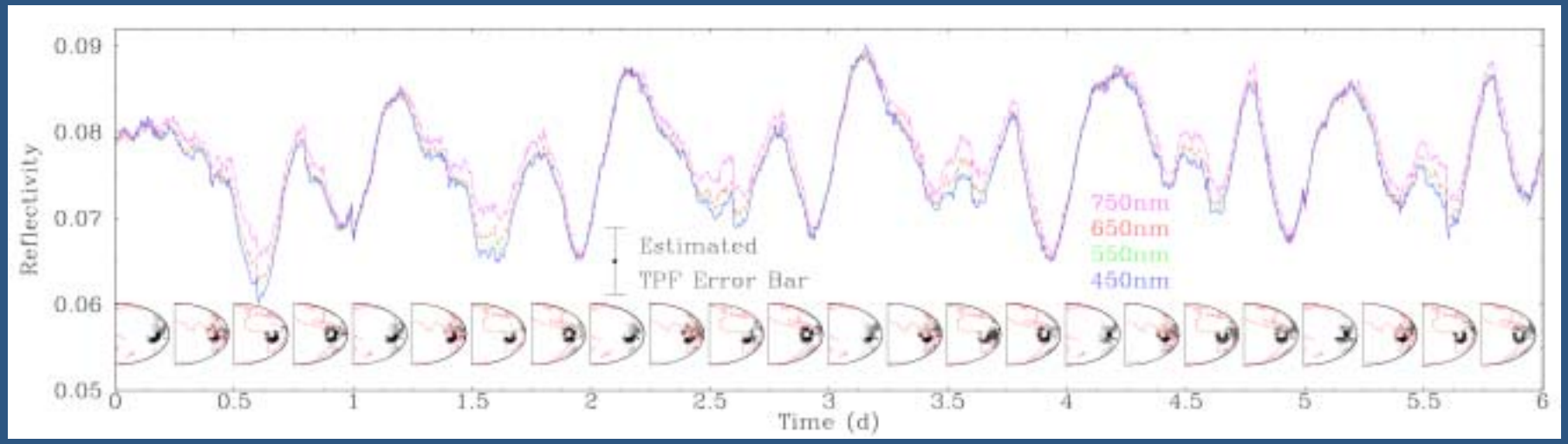
PASP 36(1924)261



reflection spectrum. The Martian spectra of the dark regions so far do not give any certain evidence of the typical reflection spectrum of chlorophyl. The amount and types of vegetation required to make the effect noticeable is being investigated by suitable terrestrial exposures.

Astrobiology indeed in 1924 !

Expected daily change of the reflected light from the earth

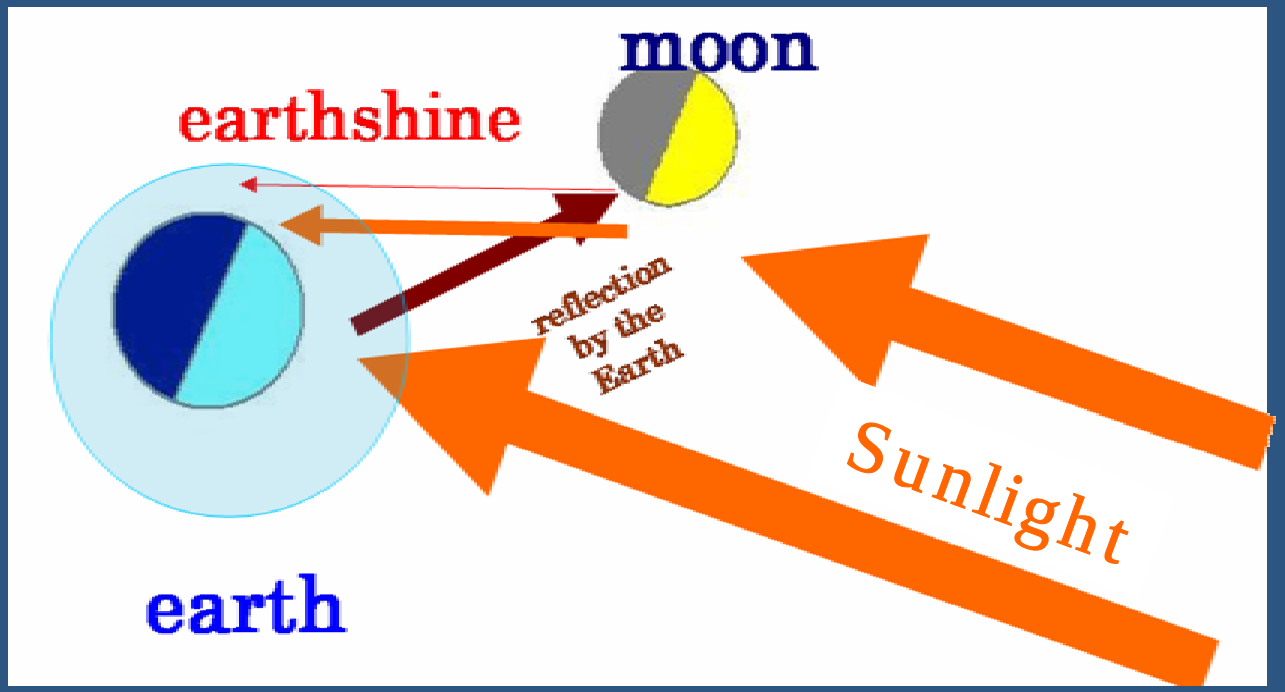


Ford, Seager & Turner: Nature 412 (2001) 885

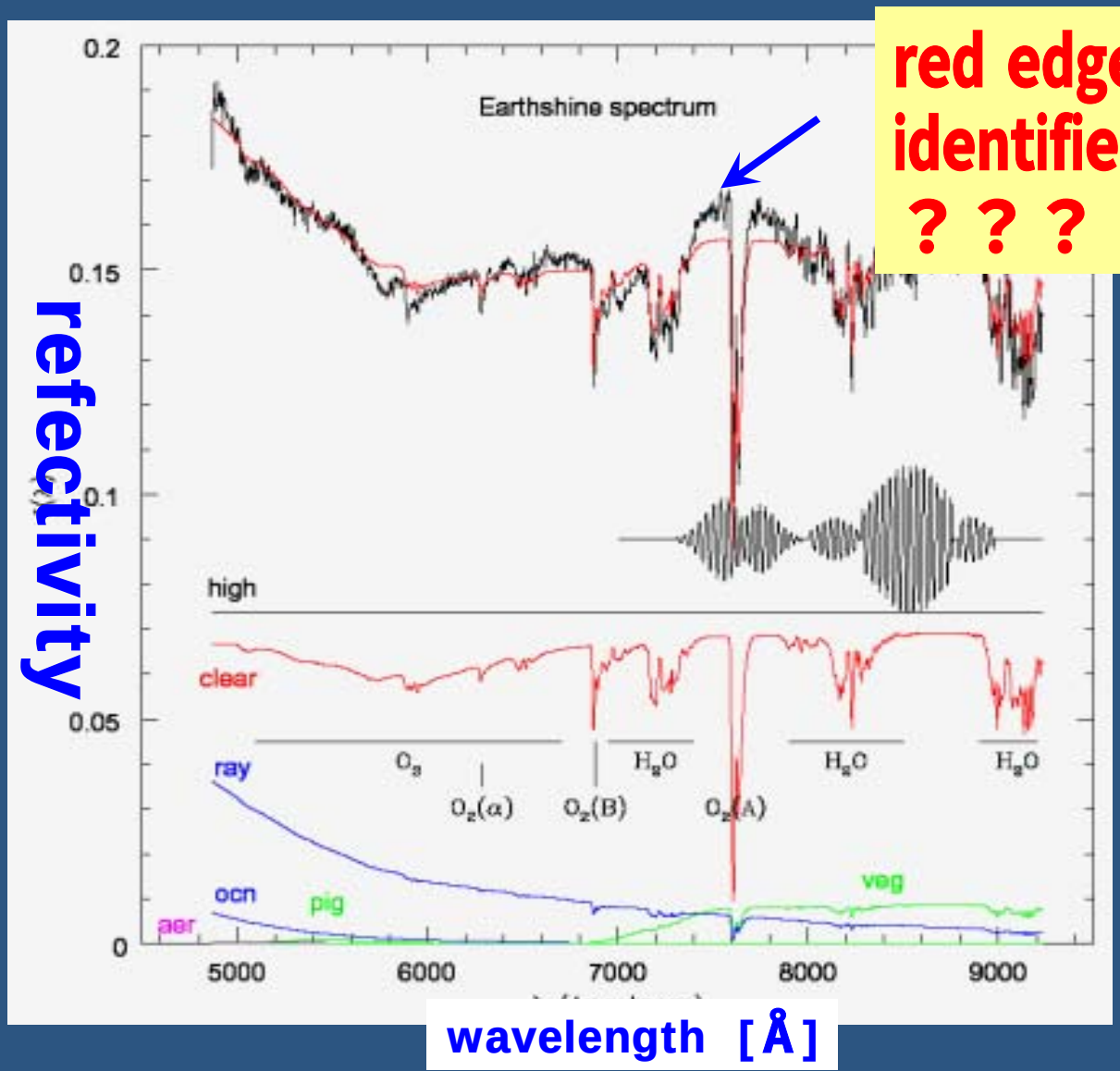
- ***Assume*** **that the earth's reflected light is completely separated from the Sun's flux !**
  - **TPF (Terrestrial Planet Finder) in (10～20) years from now ?**
- ***Periodic change of 10 % level*** **due to different reflectivity of land, ocean, forest, and so on**
- **Cloud is the most uncertain factor:** ***weather forecast !***

Earthshine observation

- Spectroscopic observation of dark side of the Moon
- the red edge in the scattered light from the earth can be identified ?
- Simulated spectroscopic observation of the earth at several pc away



a previous attempt of earthshine spectroscopy: *red-edge in a pale blue dot ?*



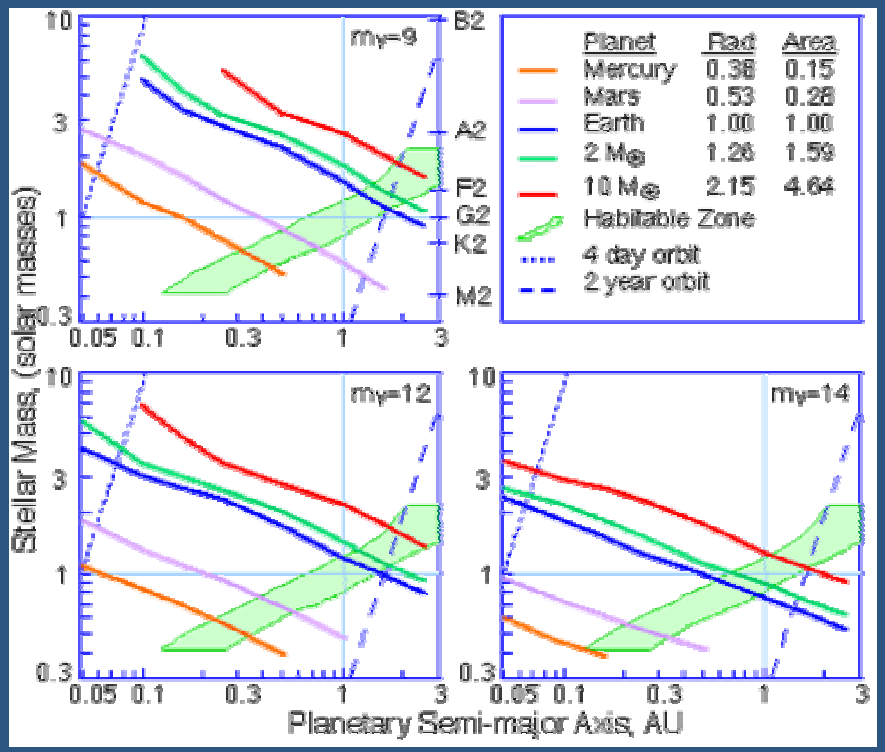
Woolf & Smith

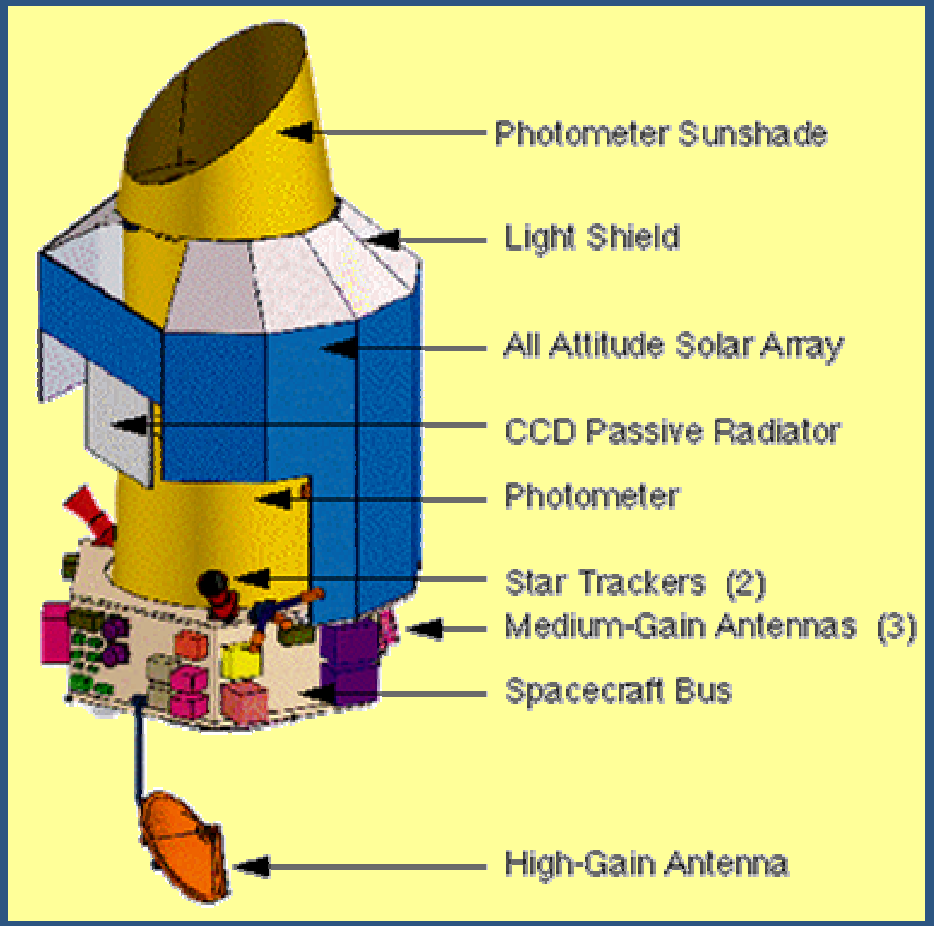
ApJ 574 (2002) 430

"The spectrum of earthshine: A Pale Blue Dot Observed from the Ground"

Kepler (NASA: launch 2008?)

differential photometry



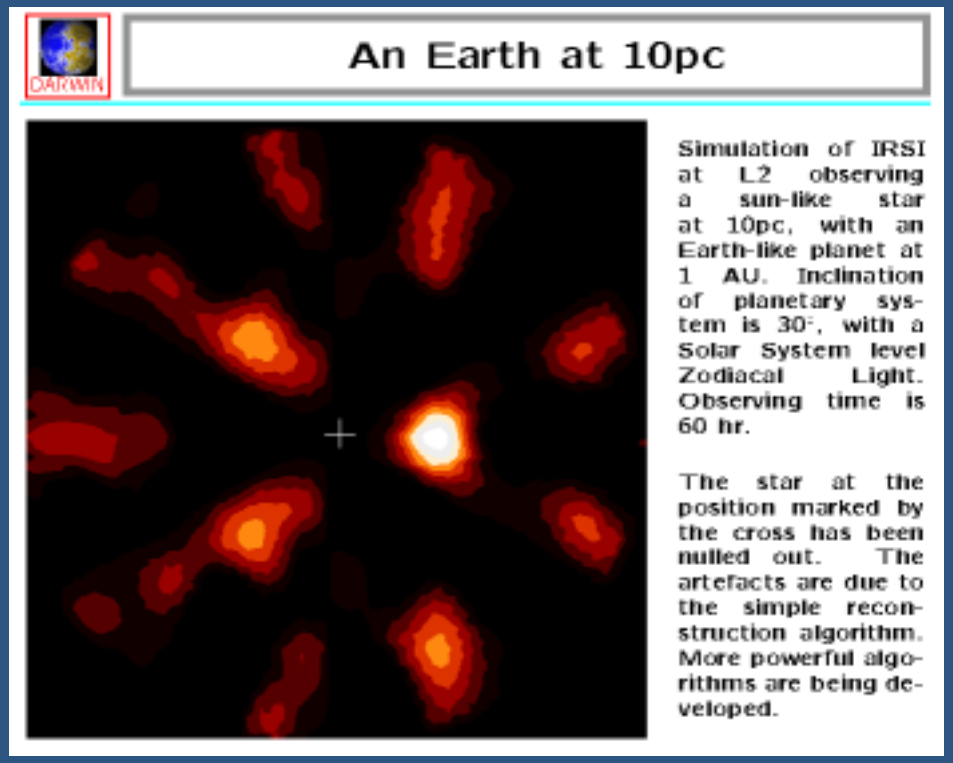


Kepler
A Search For Habitable Planets

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

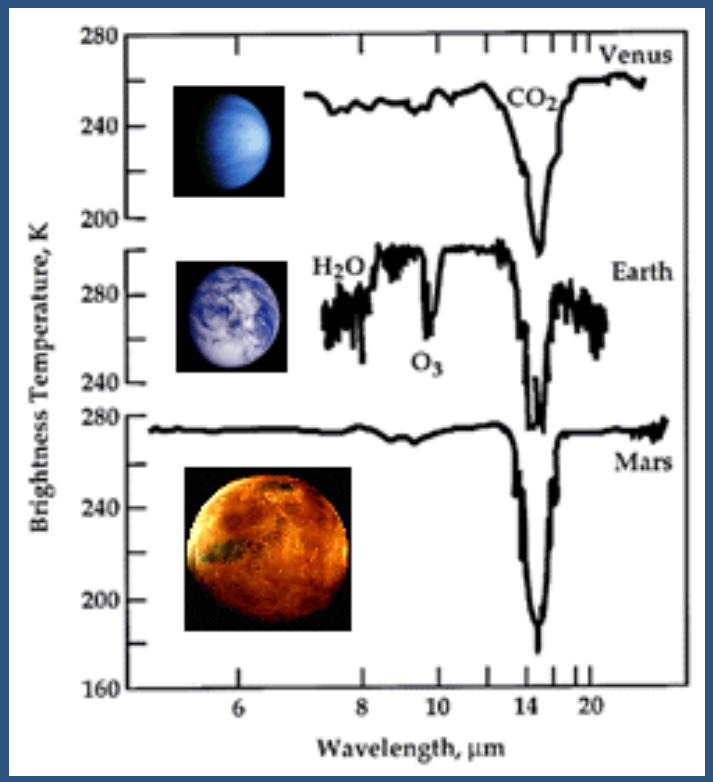
Darwin (ESA: launch after 2015)

infra-red space interferometry: imaging and spectroscopy



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

Prospects in the 21st century: from astronomy to astrobiology



- Gas planets: from discovery phase to "characterization" phase
  - Understand origin, formation and evolution
- Discovery of terrestrial planets
- Discovery of habitable planets
  - Liquid water
- **Ultra-precise spectroscopy**
- Separate the planetary emission/reflection/absorption spectra from those of stars

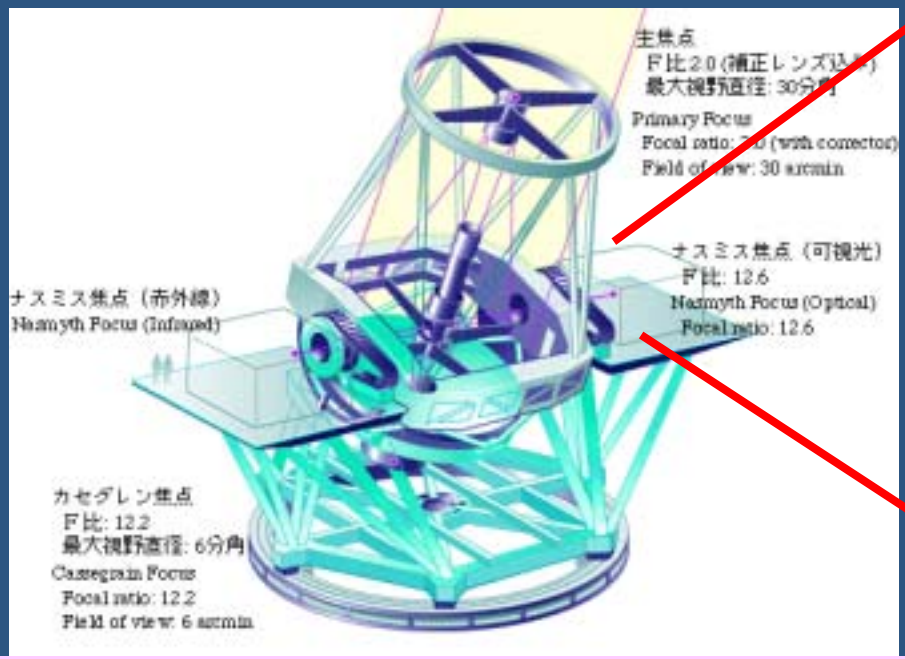
How to convince ourselves of the presence of life simply from remote observations ? Biomarker !!!

Thanks !

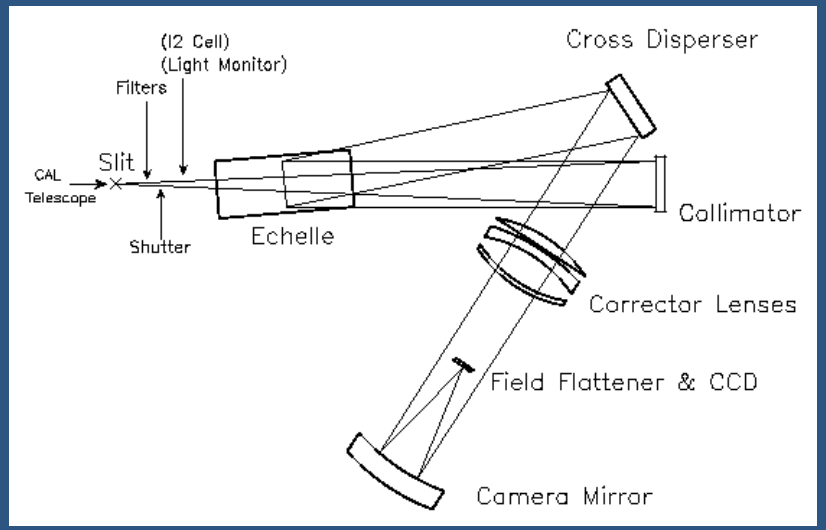
This presentation PDF file is located at

http://www-utap.phys.s.u-tokyo.ac.jp
/~suto/mypresentation_2004e.html

HDS (High Dispersion Spectrograph) at Subaru

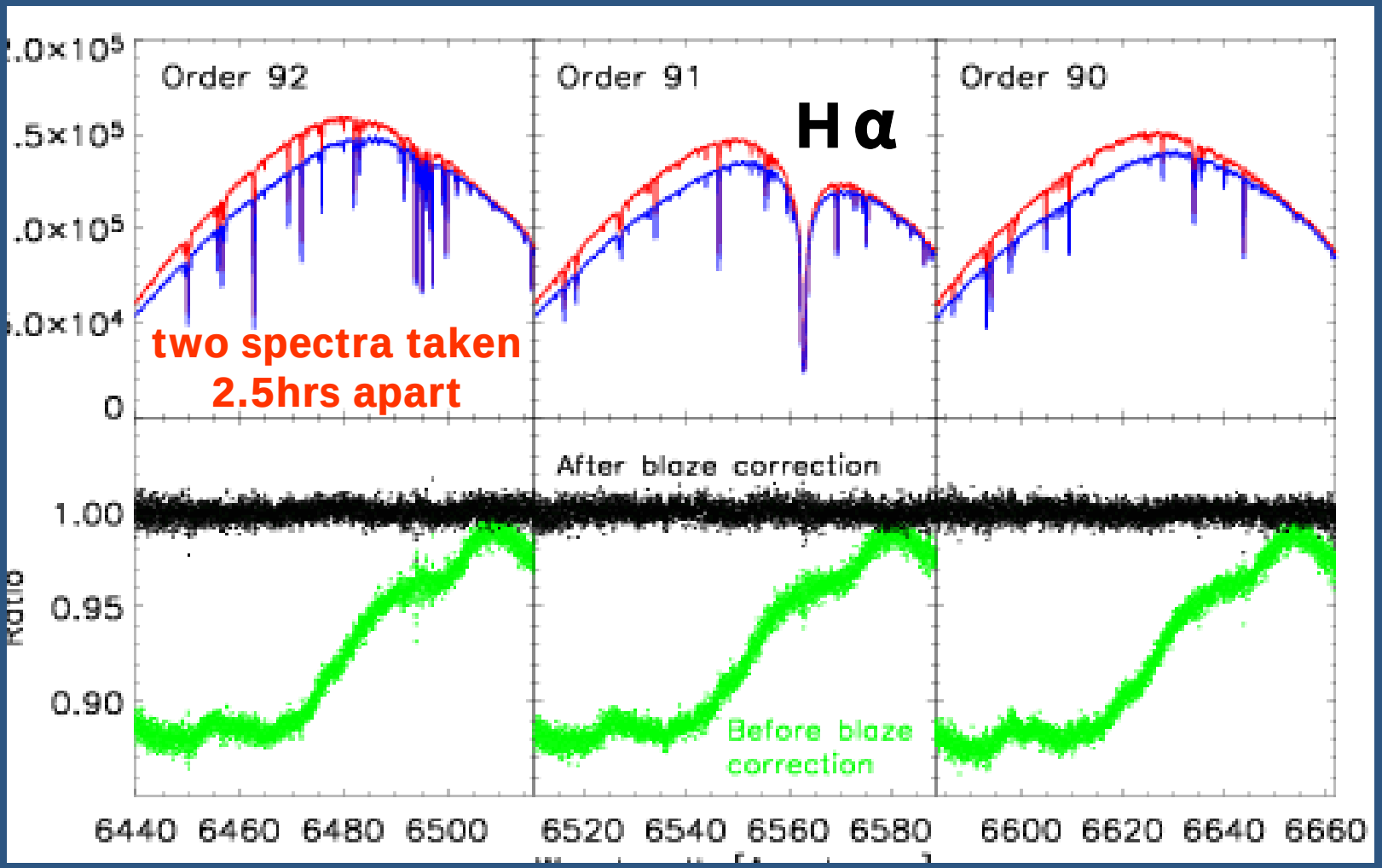


CCD: 4.1k x 2k x 2
13.5μm/pixel, 0.12”/pixel
Gain: 1.7e$^-$/ADU
Readout time: 70sec
Saturation level: 50000e$^-$
$\lambda/\Delta\lambda$=50000



HD209458 Subaru/HDS spectrum

Response function of spectrograph (blaze function)

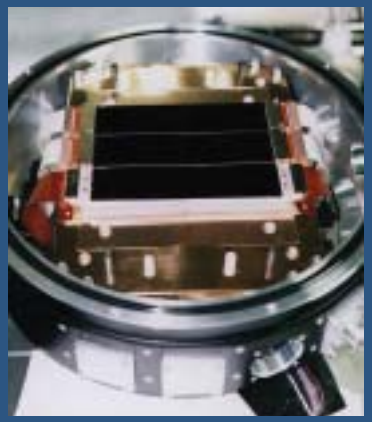


Wavelength [Å]

Winn et al. (2004)

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.



expected number of transits

number of stars of radius R_*

geometrical probability for the transit

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

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