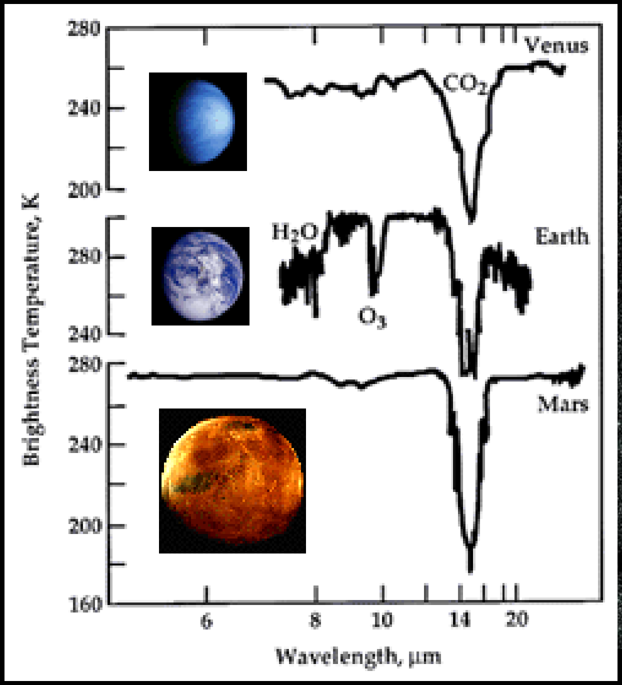
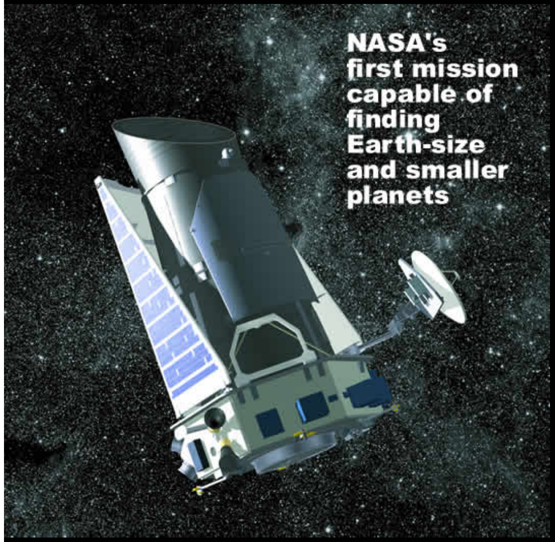
Extrasolar planets





Yasushi Suto *Department of Physics, the University of Tokyo*

Summer School of KEK theory group @Hakuba
July 30 and 31, 2007

Plan of the talk

Ⅰ why extrasolar planets ?

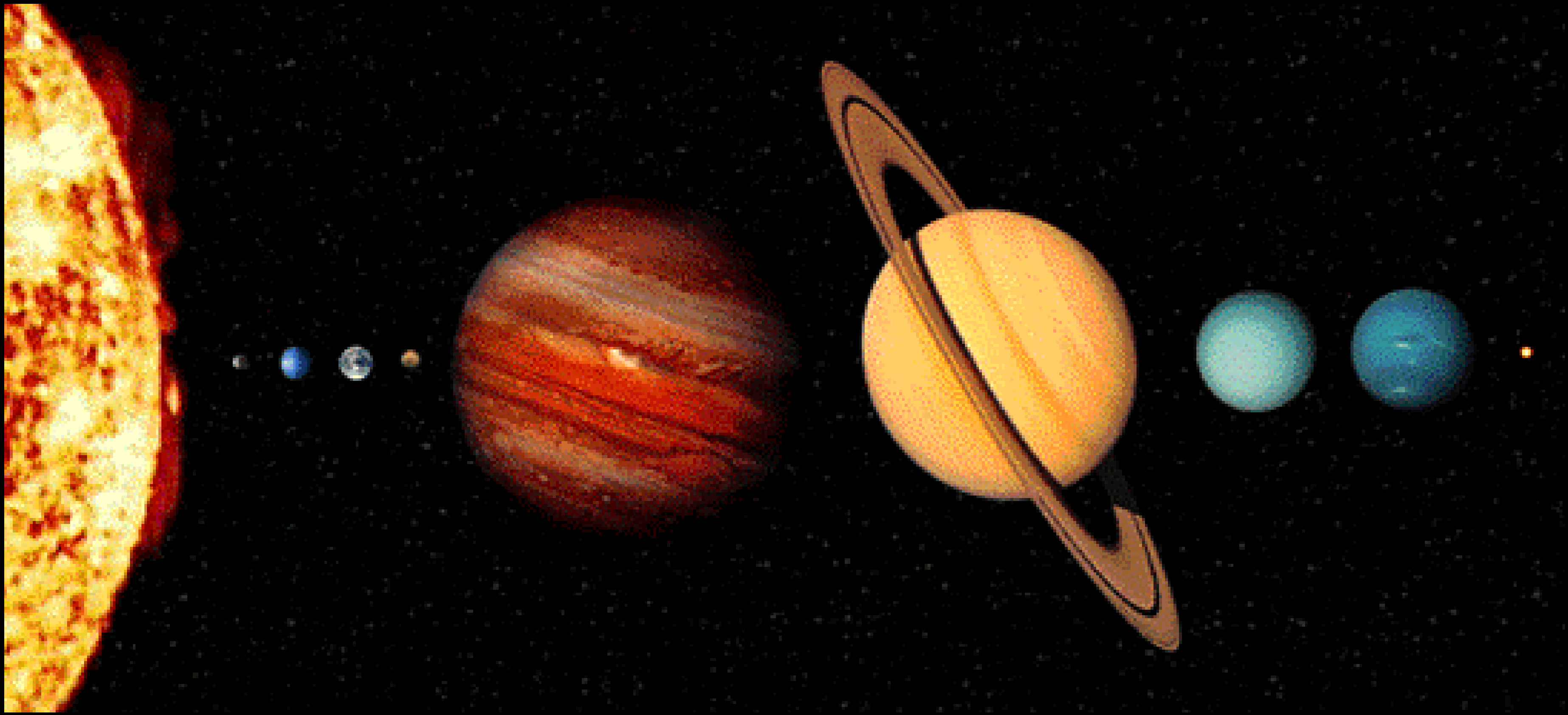
Ⅱ detection methods

Ⅲ transiting planet projects at University of Tokyo

Ⅳ the Rossiter effect

Ⅴ toward astrobiology

I why extrasolar planets ?



Search for extrasolar planets

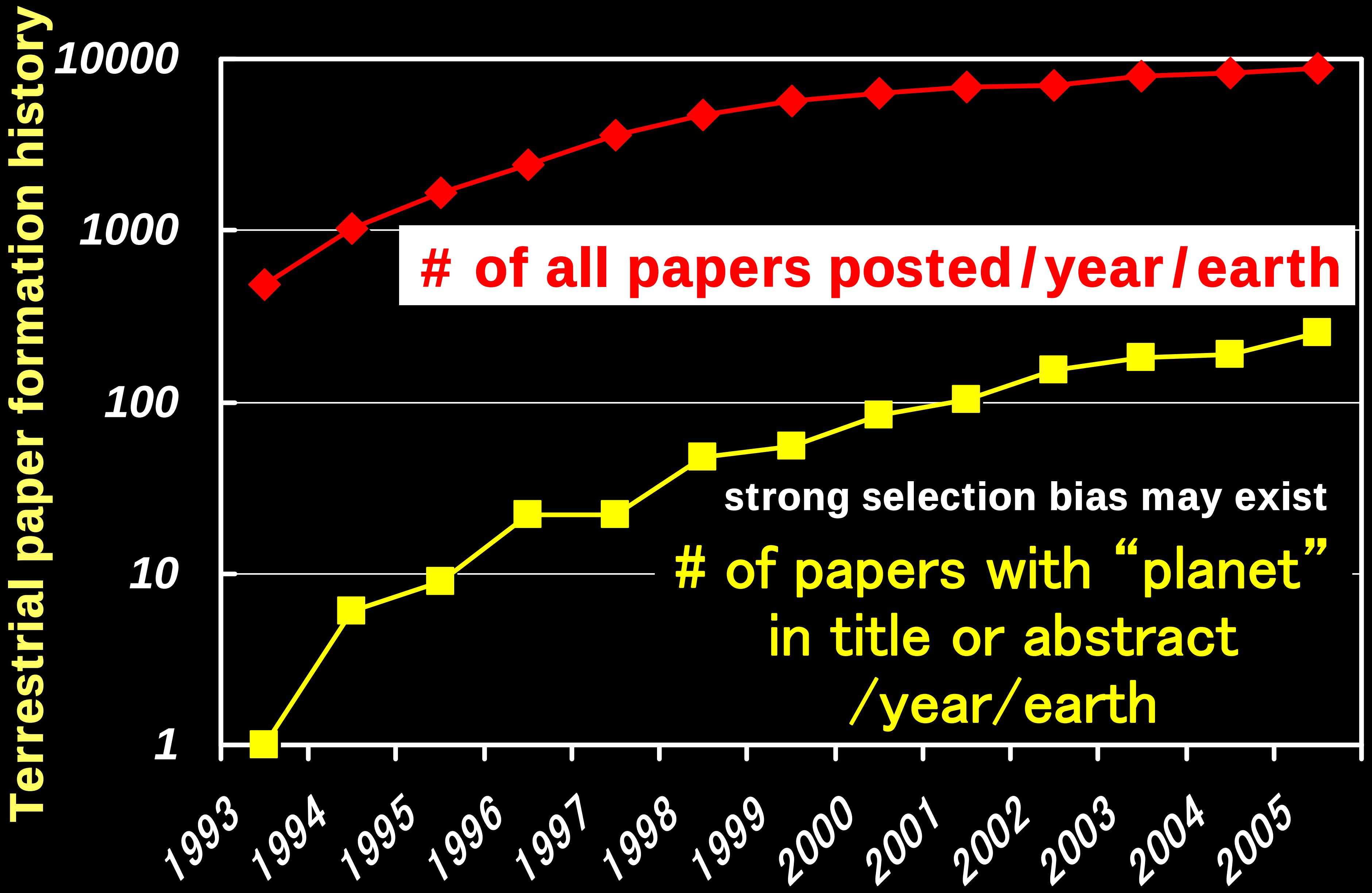
- the goal: ***Are we alone ?***
  - origin of the earth
  - origin of the Solar System
  - ***habitable*** planets ⇒ origin of life
  - signature of *extra-terrestrial life* ?
  - ***extra-terrestrial intelligence ?***

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

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

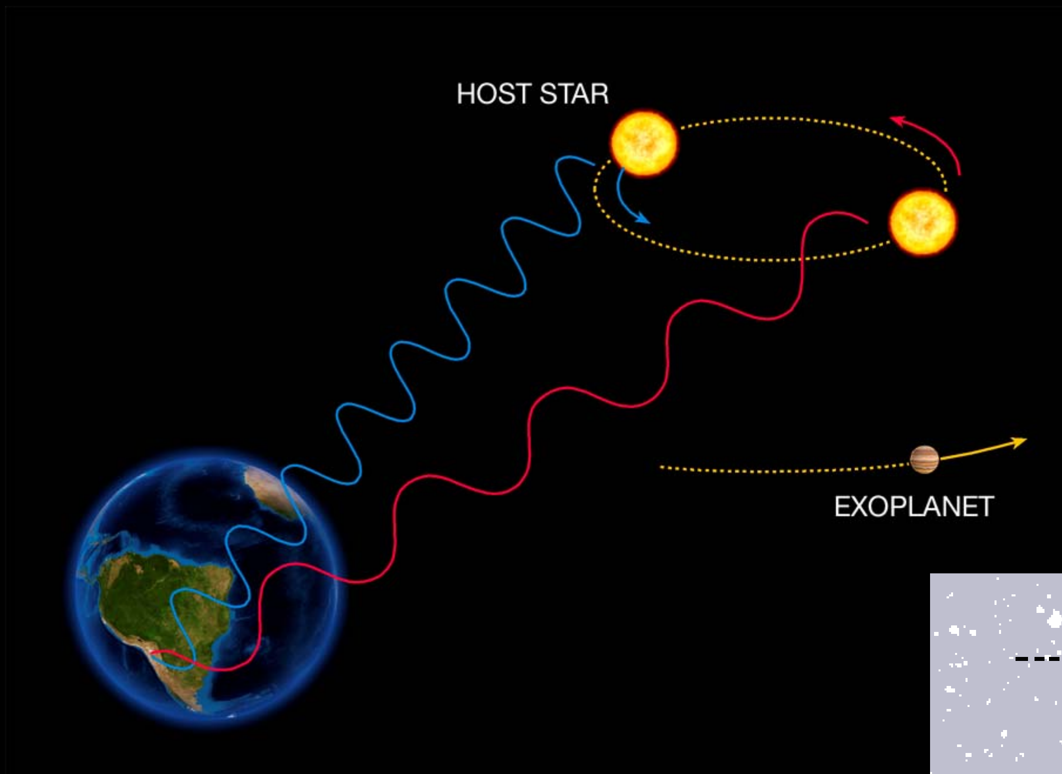
“Evolution” of extra-solar planet research



The ***first*** astro-ph paper with a word “planet” in its abstract

- astro-ph/9309052
- MACHO discovery paper by C.Alcock et al.
- **Possible Gravitational Microlensing of a Star in the Large Magellanic Cloud**
  - … A less exotic alternative is normal matter in the form of bodies with masses ranging from that of a large planet to a few M_{sun}…

Ⅱ detection methods



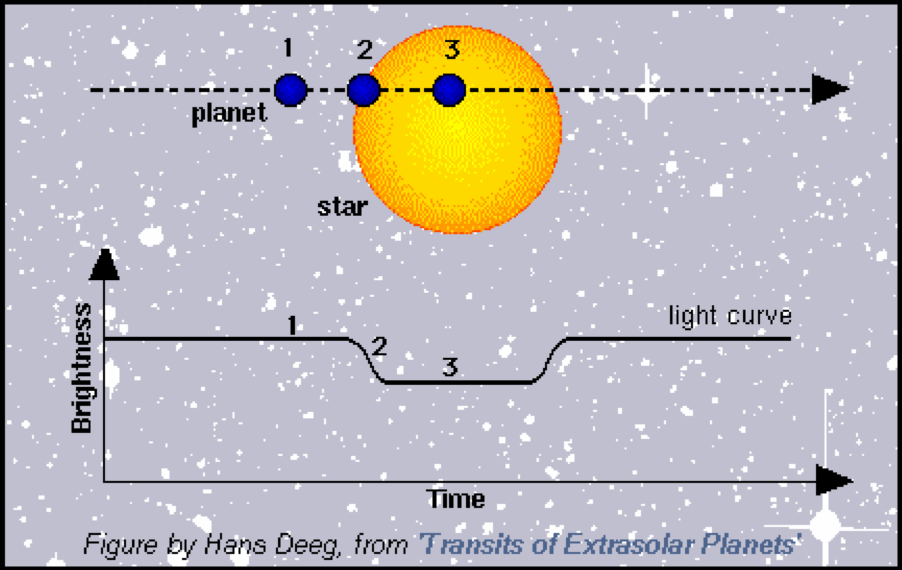
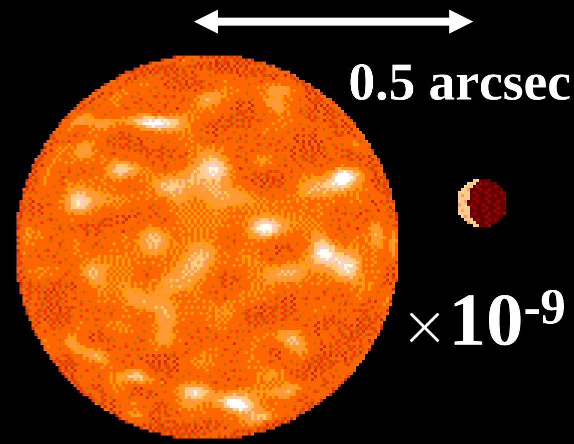


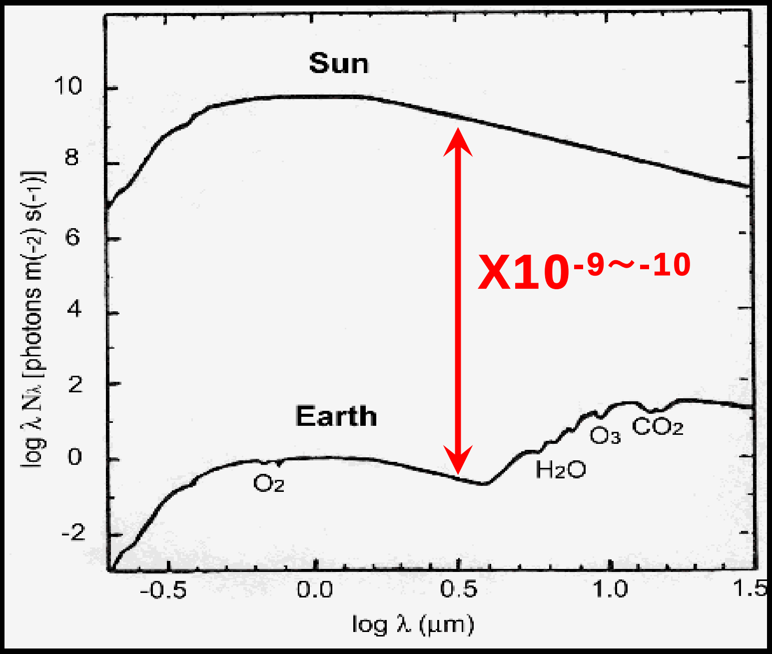
Figure by Hans Deeg, from 'Transits of Extrasolar Planets'

Direct imaging ?

Jupiter at a distance of 10 pc

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

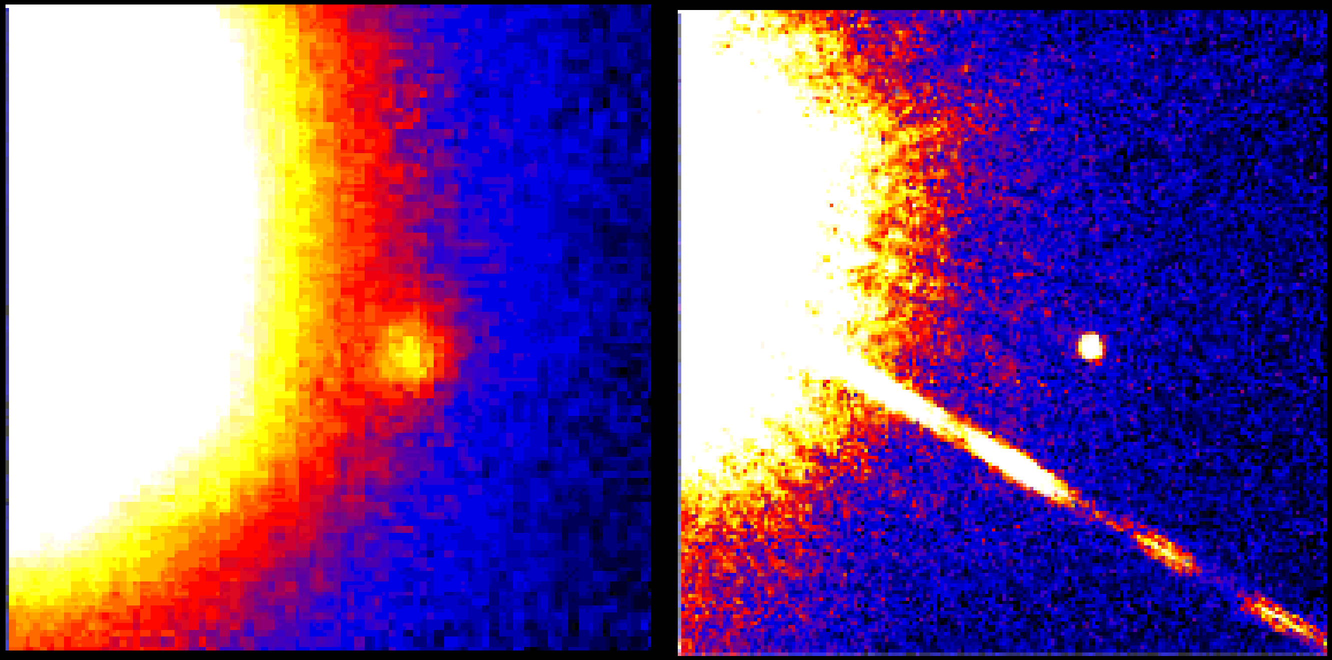




need to detect a 10^{-9} times darker object than the main star which locates within a typical seeing scale of the ground observation !

⇒ Just impossible！

An ***observed*** brown dwarf: Gliese 229b



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

(Nakajima et al. 1995)

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

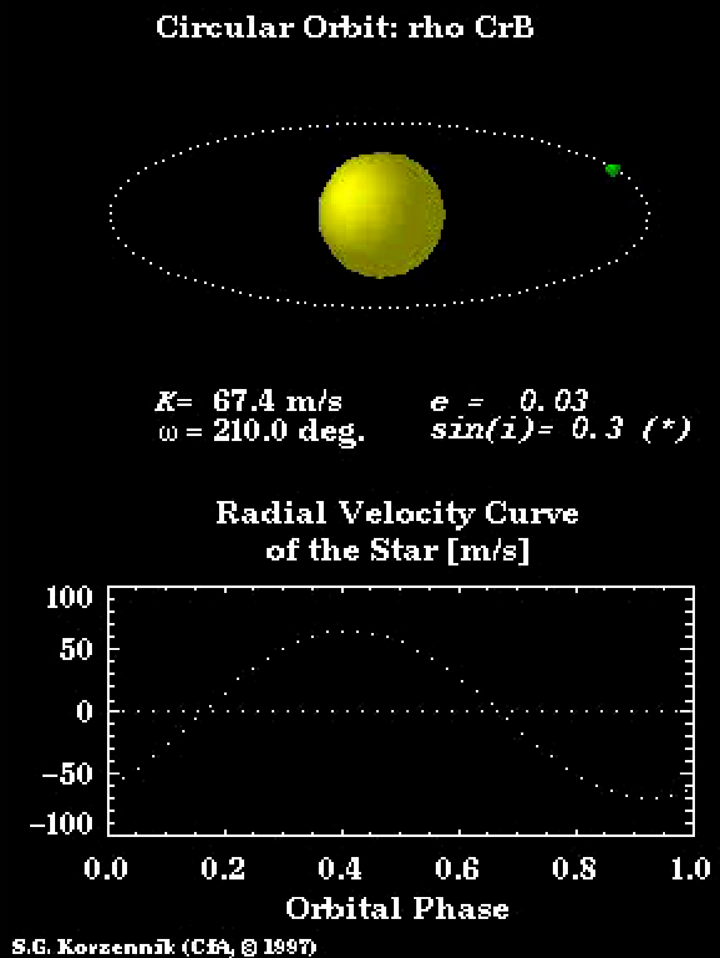
A brief history of extrasolar planets

- **1995 :** the first extrasolar planet around the main sequence star 51 Pegasi (Mayor & Queloz)
- **1999 :** transit of a known planet around HD209458 (Charbonneau et al., Henry et al.)
- **2001 :** Na in the atmosphere of HD209458b
- **2003:** first discovery of a planet by transit method *alone* (1.2 day orbital period: OGLE)
- **2005:** first detection of the spin-orbit misalignment via the Rossiter effect (Winn et al.)
- **2007:** habitable super-Earth ? (Udry et al. 2007)
- *～250 extrasolar planets* are reported (July 2007)

http://exoplanets.org/

Radial velocity of a star perturbed by a planet

- Even if planets are not directly observable, their presence can be inferred dynamically

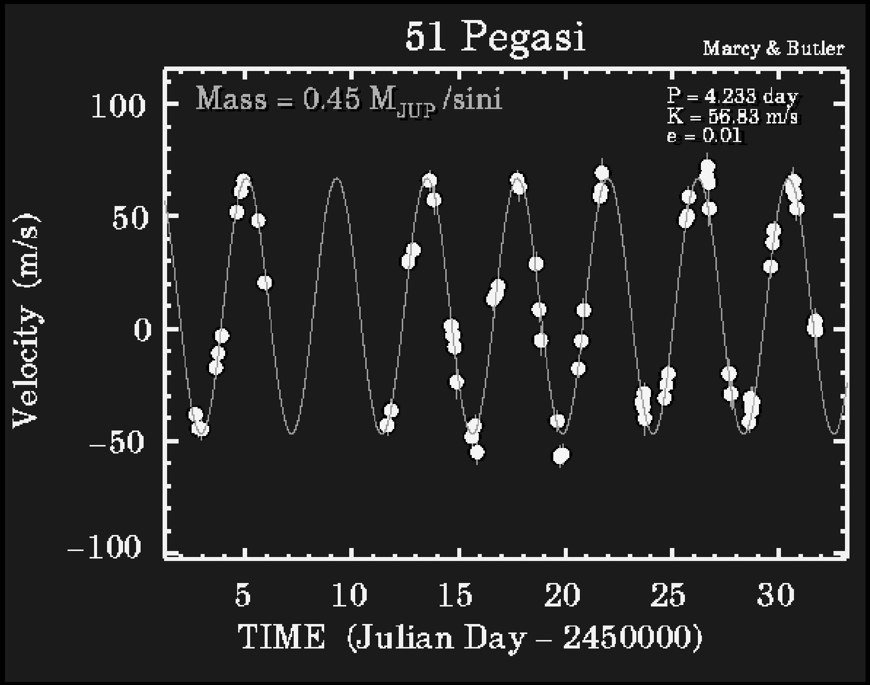


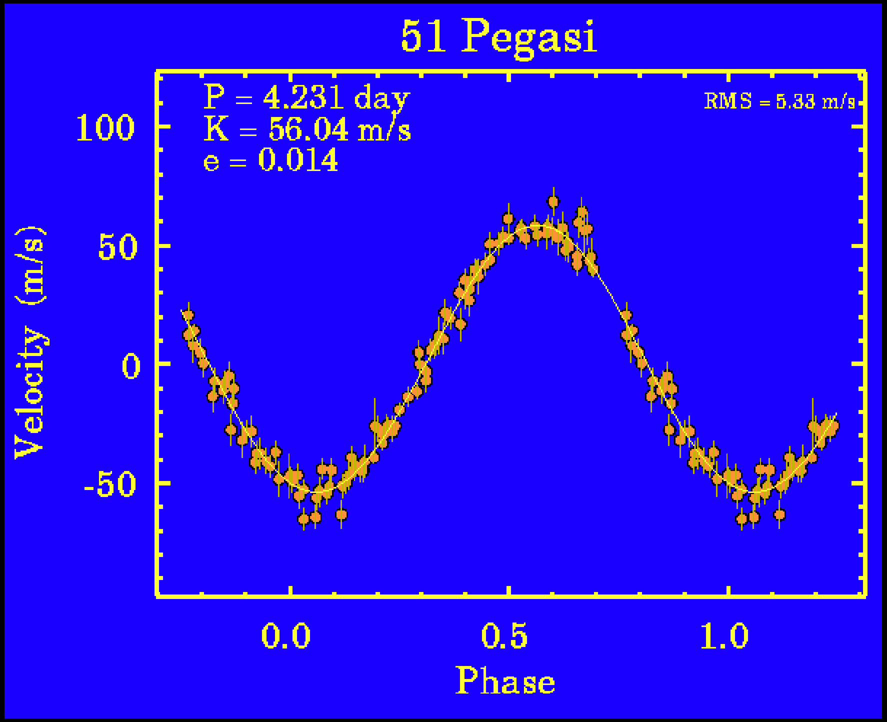
- velocity modulation of the Sun:
  - 12.5 m/s (Jupiter)
  - 0.1 m/s (Earth)
- an accuracy of 1m/s achieved from the ground observation

⇒ the major method of (Jovian) planet search

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)

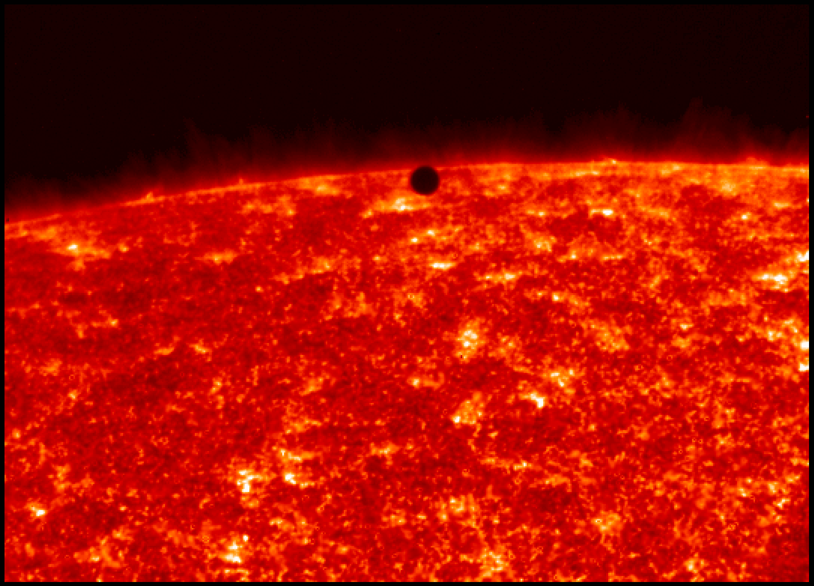




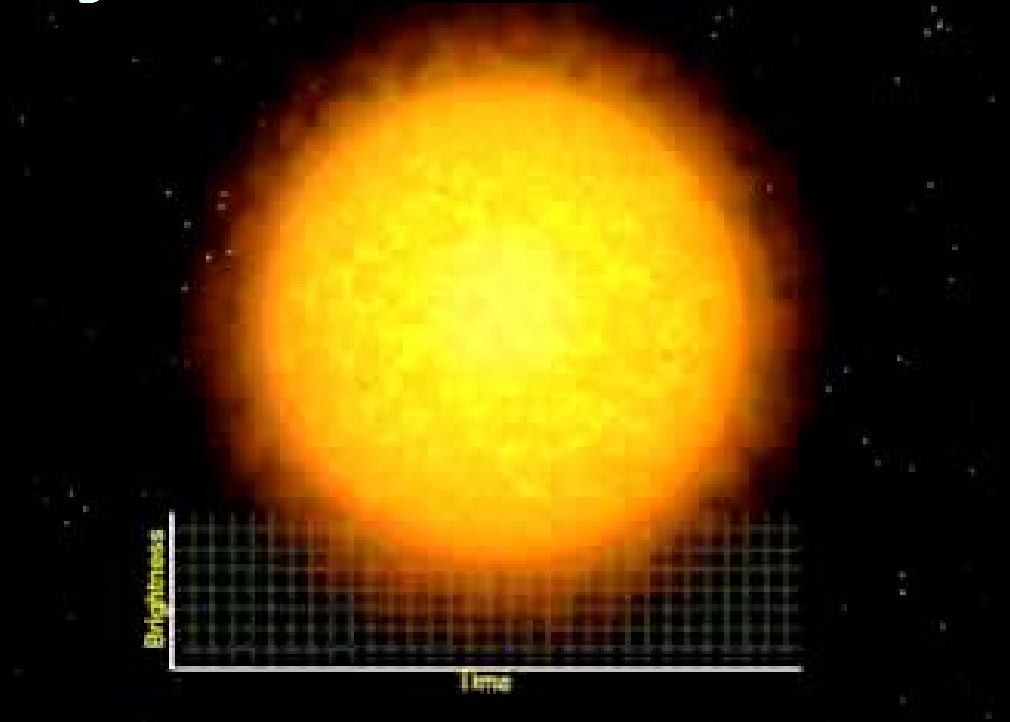
P=4.2 days !

Pioneers of radial velocity measurements

Stellar light curve variation due to planetary transit



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



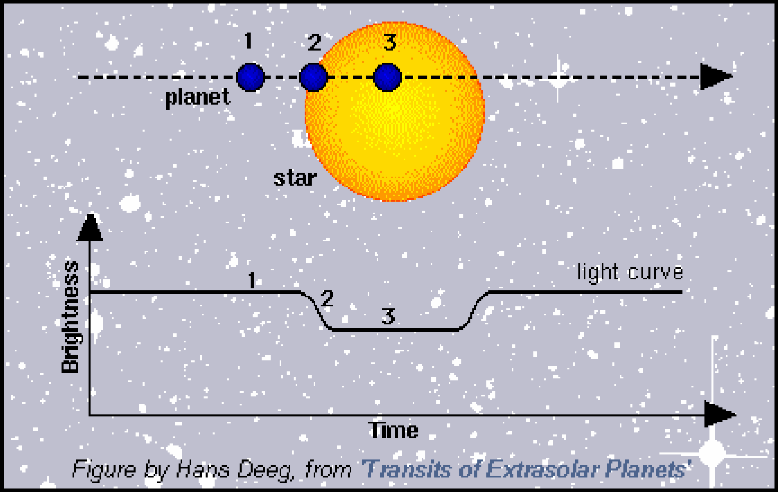
http://hubblesite.org/newscenter/archive/2001/38/

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



- 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:

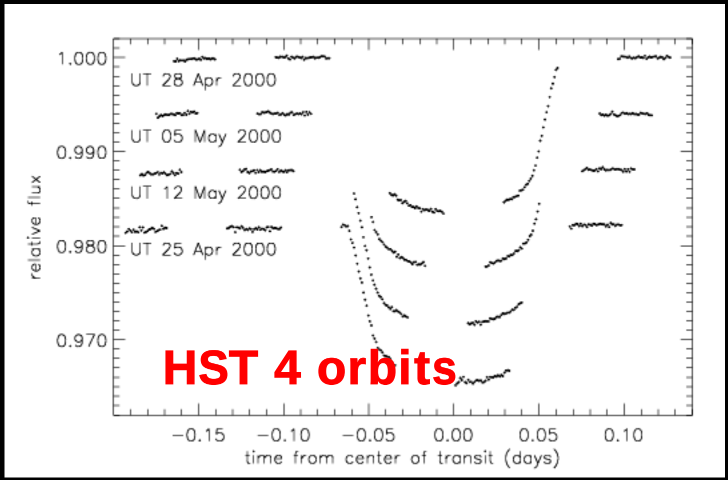
$$10\% \ (0.05\mathrm{AU}/a_{orbit})(R_{star}/R_{Sun})$$

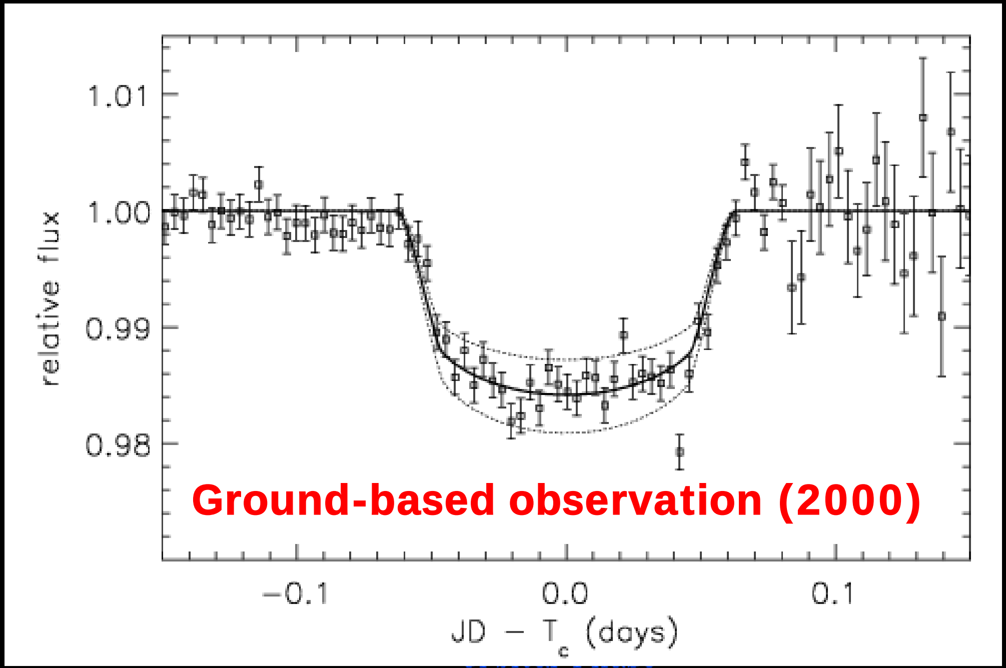
- Small flux variation:

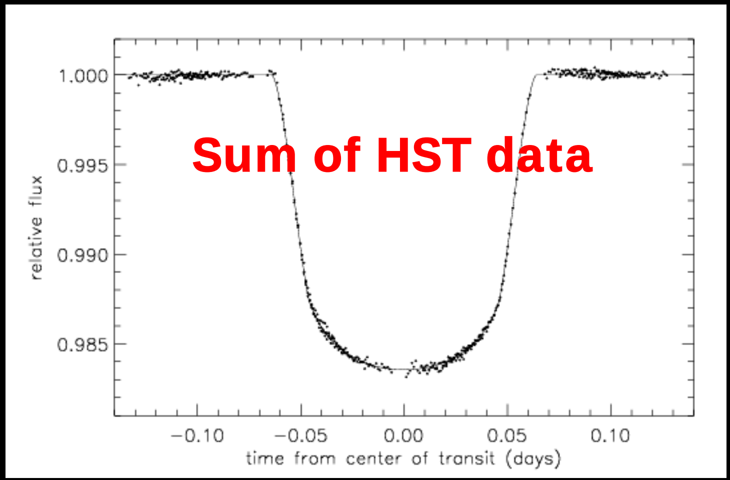
$$1\%(R_{planet}/R_{Jupiter})^2(R_{Sun}/R_{star})^2$$

the first discovery of a transiting 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)

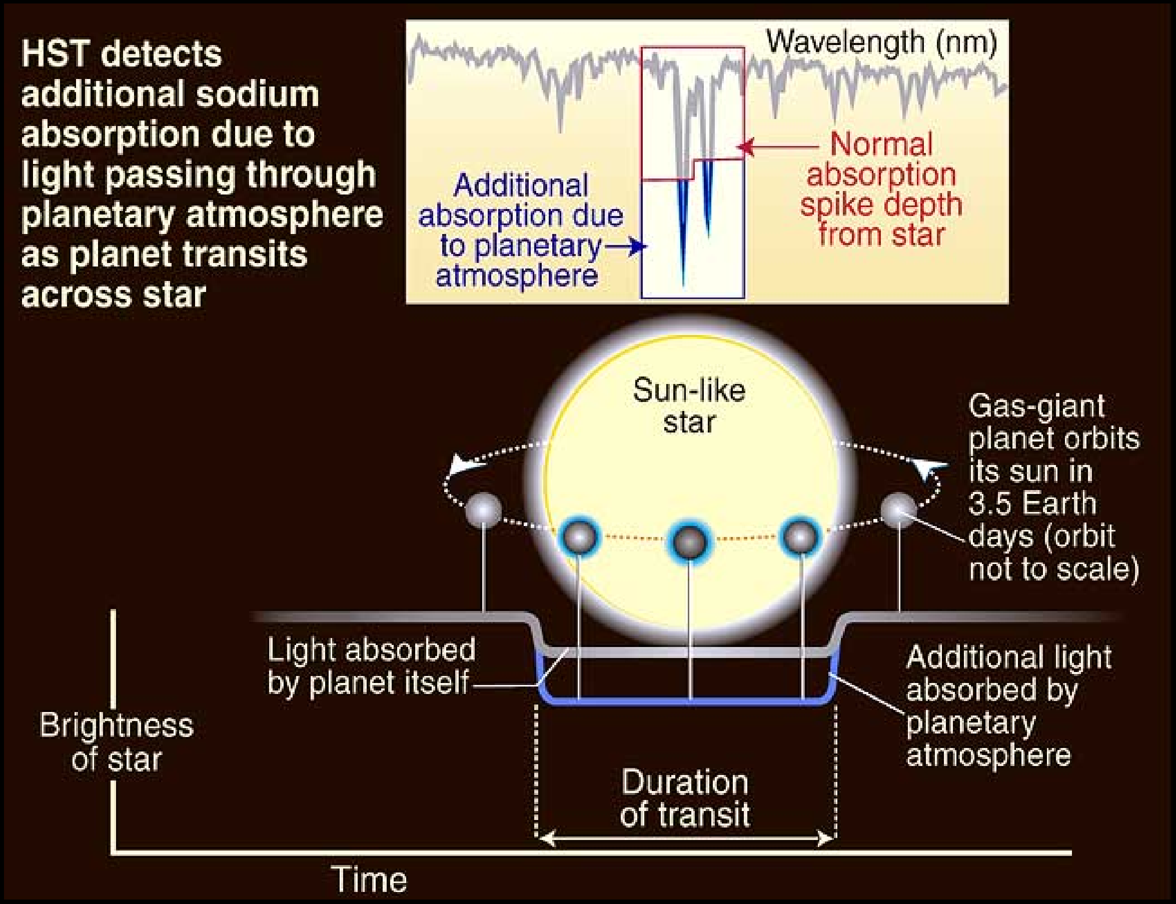
Estimated parameters of HD209458b

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

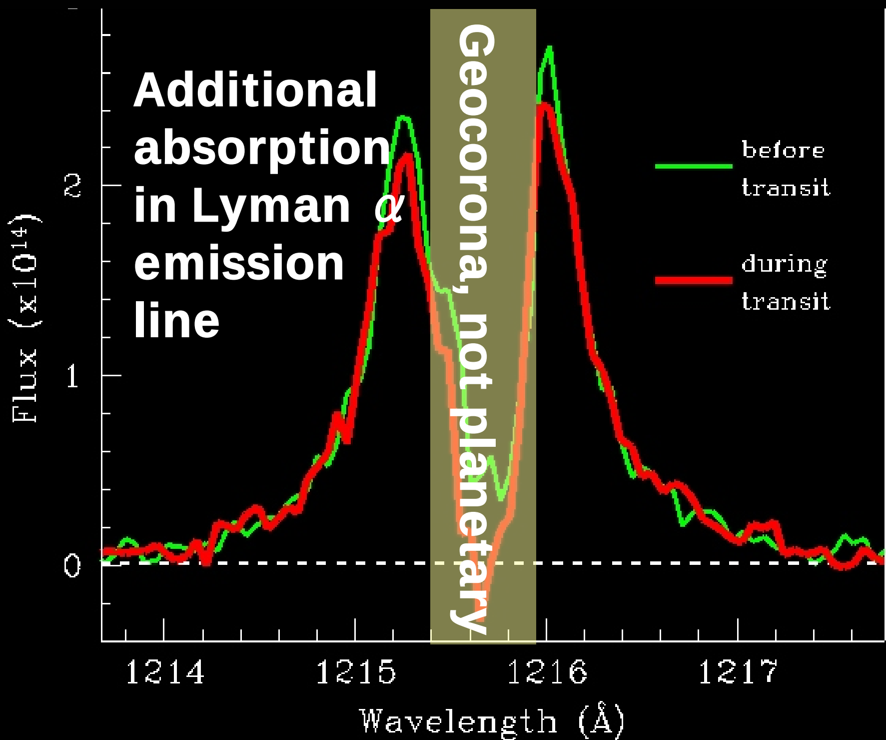
http://hubblesite.org/newscenter/archive/2001/38/

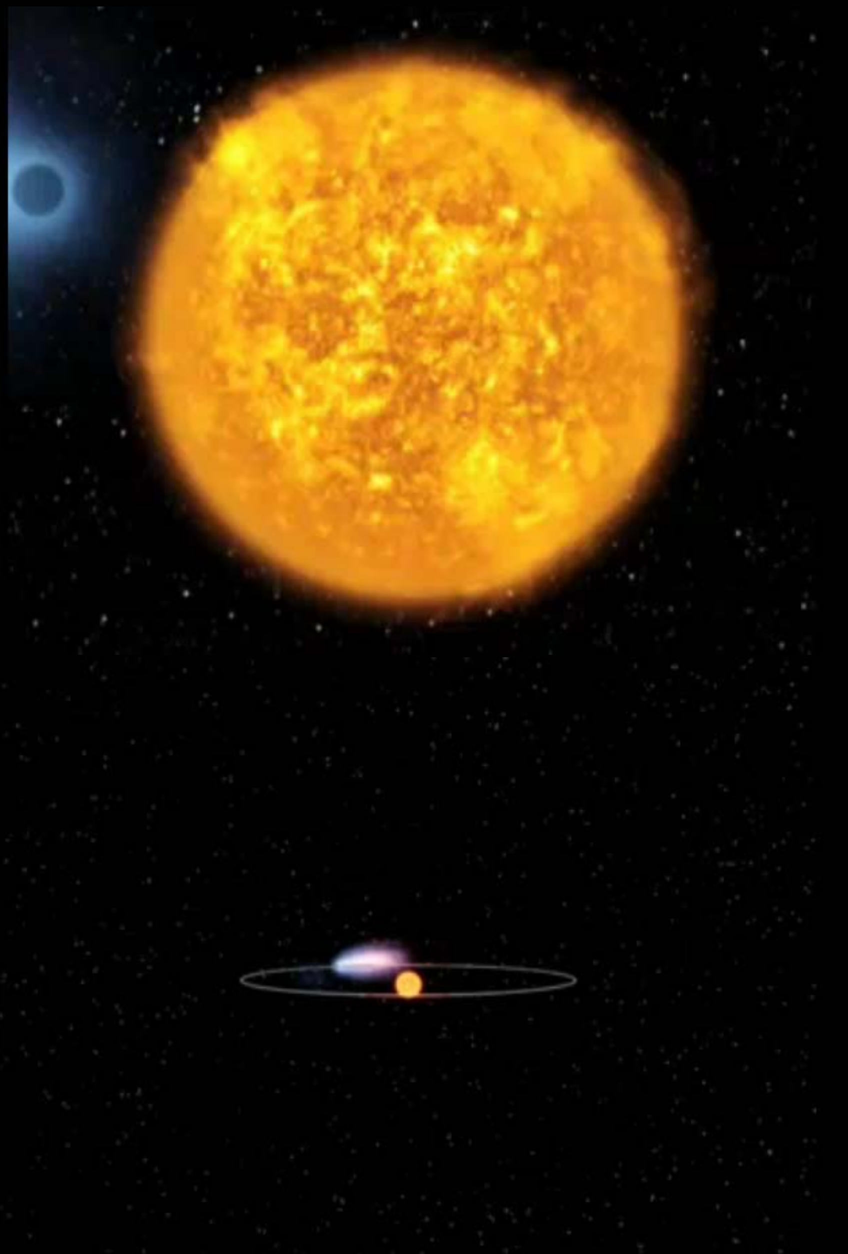


- **Nov. 2001: additional sodium absorption during the transiting phase (Charbonneau et al. 2002)**
- **The first detection of atmosphere of an extrasolar planet**

HD209458b: evaporating planet ?

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

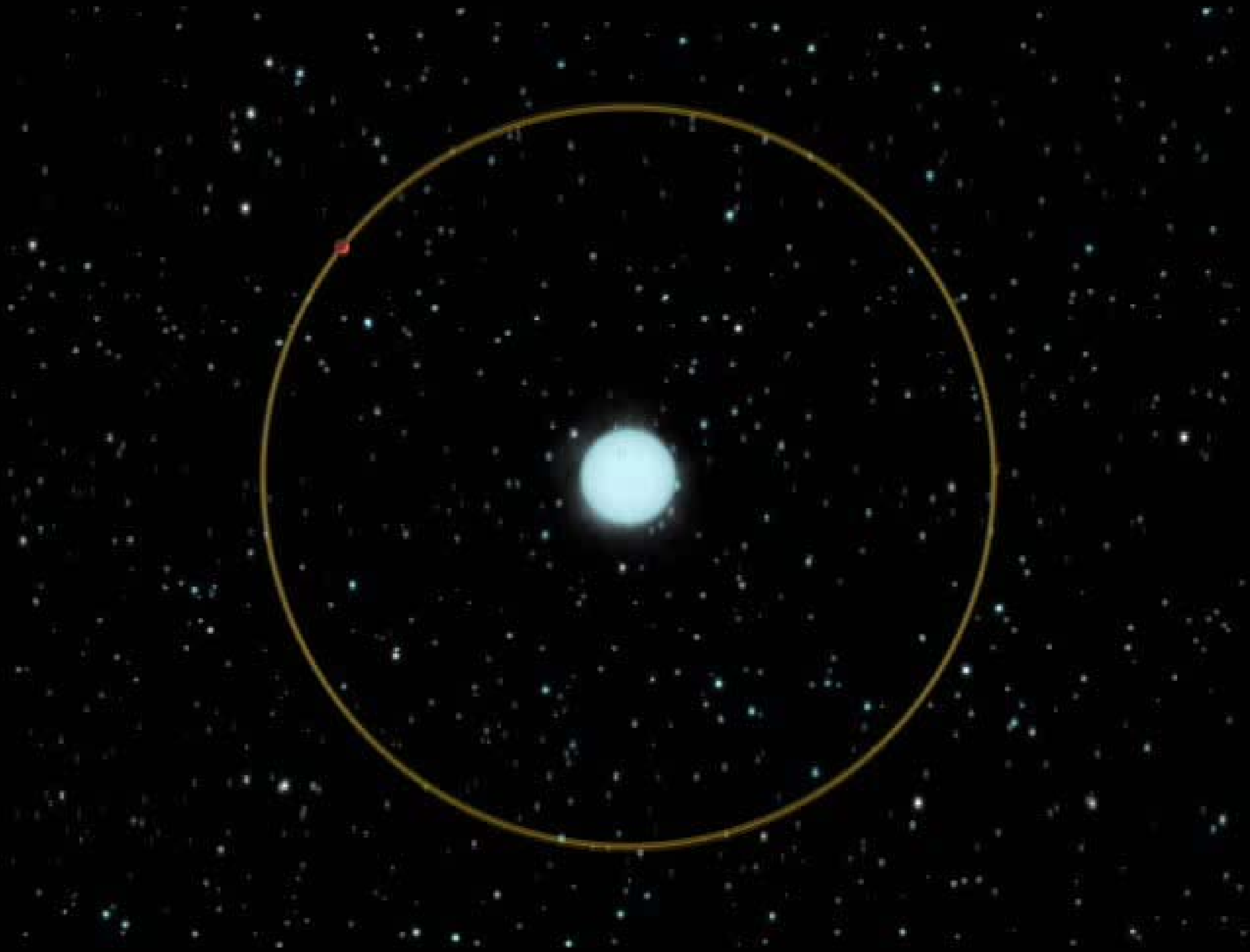




Vidal-Madjar et al. Nature 422(2003)143

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

Secondary eclipse of HD209458b (Spitzer infrared satellite)



http://www.spitzer.caltech.edu/Media/releases/ssc2005-09/release.shtml

Ⅲ transiting planet projects at University of Tokyo

多天体近赤外撮像分光装置 (MOIRCS) ④
近赤外線の撮像及び分光観測を行う。

近赤外線分光撮像装置 (IRCS) ④
波面補償光学装置を生かした高い解像力と感度による撮像観測や、2万分の1の波長差を識別できる分光観測を行う。

コロナグラフ撮像装置 (CIAO) ④
明るい天体のすぐ近くにある暗い天体の画像を撮影するのが得意な装置で、太陽系外の惑星の発見に威力を発揮する。

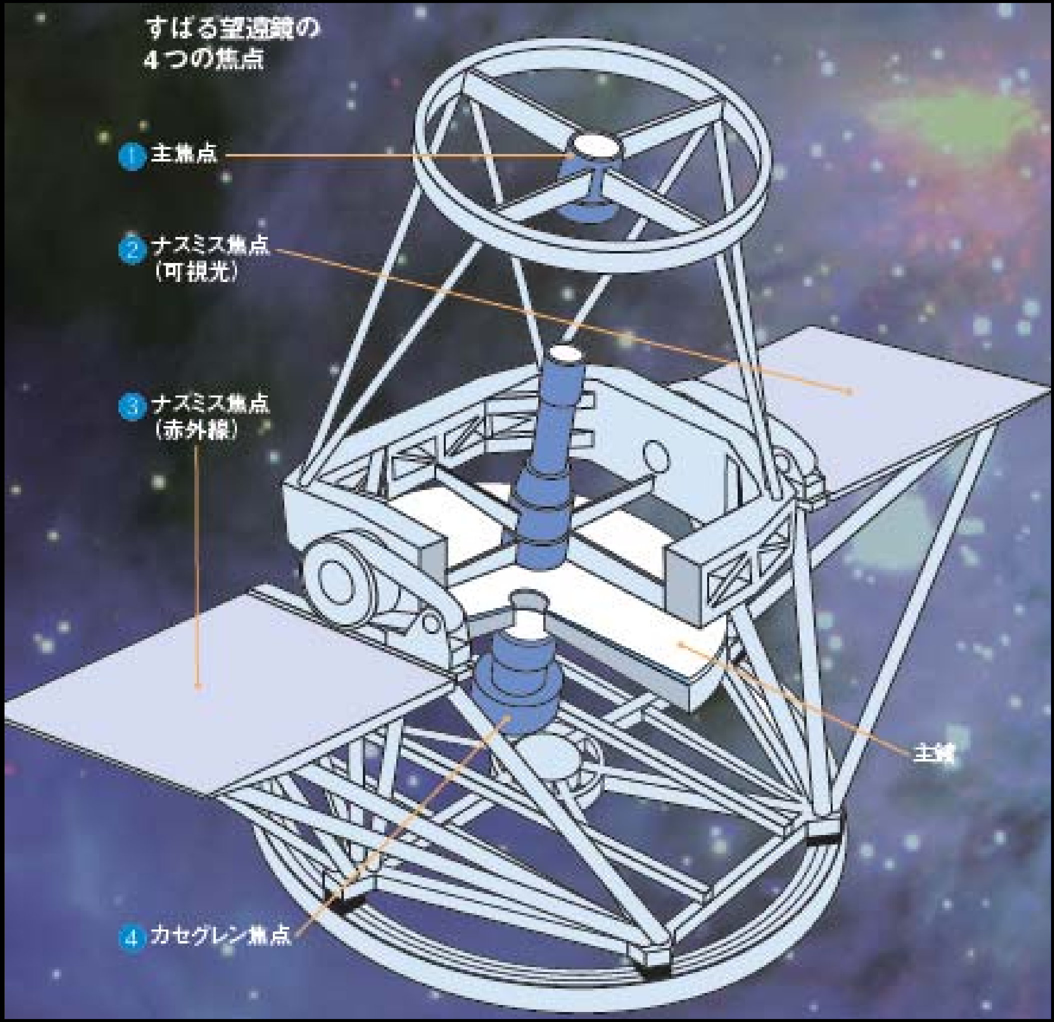
冷却中間赤外線分光撮像装置 (COMICS) ④
波長 10μmと20μmの中間赤外線で観測を行う装置で、惑星系の形成過程や系外銀河の大規模な星形成現象、また星間空間の固体成分であるダストの形成過程を調べることができる。

微光天体分光撮像装置 (FOCAS) ④
可視光で高い感度の観測を行う基本装置で、視野内の 100 個の天体のスペクトルを同時に撮影できる機能をもち、宇宙の果て近くにある銀河までの距離を効率よく調べられる。

主焦点カメラ (Suprime-Cam) ①
月の直径と同じ視野を一度に撮影でき、銀河の誕生・進化や宇宙構造の研究、太陽系外縁部の小天体探索に威力を発揮する。

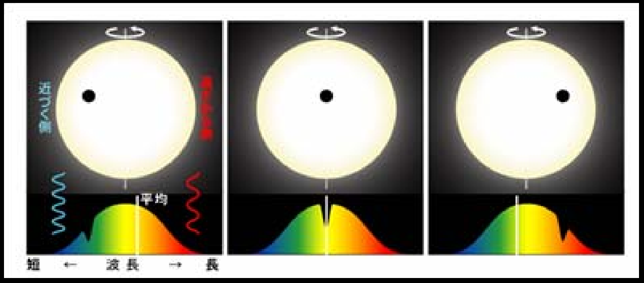
高分散分光器 (HDS) ②
可視光で 10 万分の 1 の波長差を識別できる装置で、古い星の元素組成を調べて宇宙における元素の進化を研究したり、クエーサーの吸収線を調べて銀河間ガスの組成や物理状態を調べる研究に用いられる。

波面補償光学装置 (AO) ④
大気のゆらぎを実時間で補正することにより、主鏡の直径によって決まる解像力 (回折限界) を実現する。

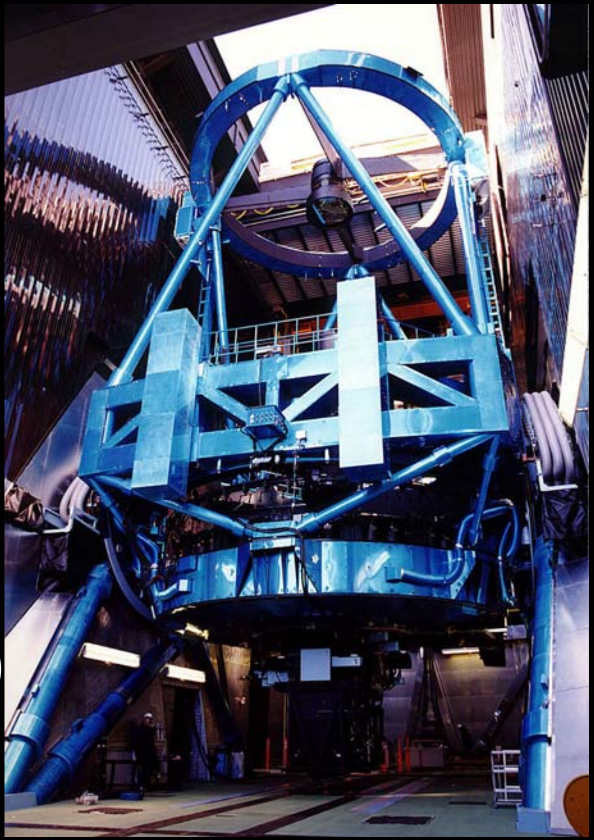


Transiting planet projects at Univ. of Tokyo

- **Search for the planetary atmosphere with Subaru**
  - the most stringent upper limits from ground-based obs.
  - Winn et al. PASJ 56(2004) 655 (astro-ph/0404469)
  - Narita et al. PASJ 57(2005) 471 (astro-ph/0504450)
- **Constraining the stellar spin and the planetary orbital axes from the Rossiter-McLaughlin effect**
  - New analytic formulae **(Ohta, Taruya & Suto 2005)**
  - First detection (Winn et al. 2005 ApJ, 631, 1215)
- **Search for reflected light from planets**
  - collaboration with Andrew Cameron (St. Andrews Univ.) & Chris Leigh (Liverpool John Moores Univ.)



Subaru observation with HDS



"Spectro-photometric search for scattered light from HD209458b"

S02B-16 on October 24 and 26, 2002

Yasushi Suto, Norio Narita (Univ. of Tokyo)

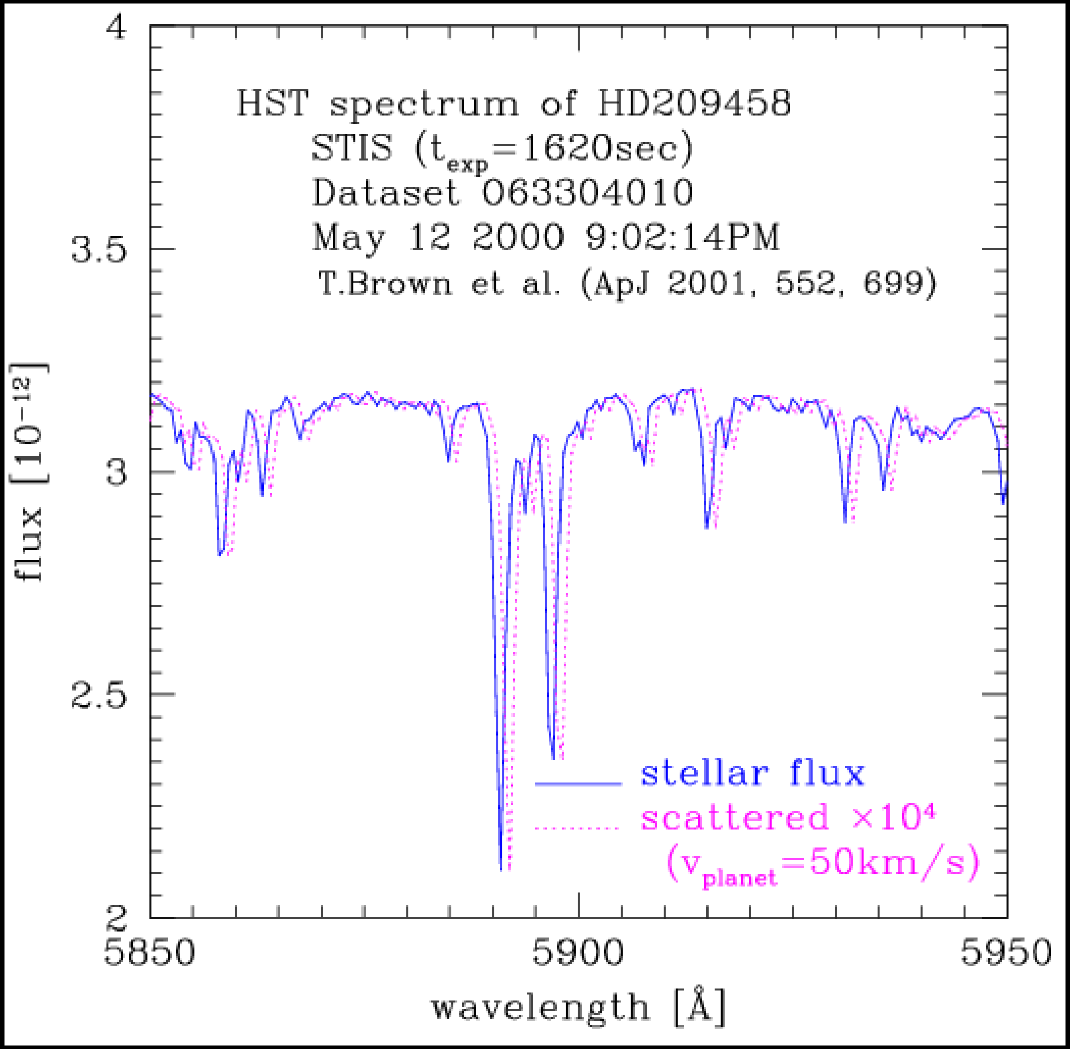
Toru Yamada, Wako Aoki (National Ast. Obs. Japan)

Bun-ei Sato (Kobe Univ.)

Edwin L. Turner (Princeton Univ.)

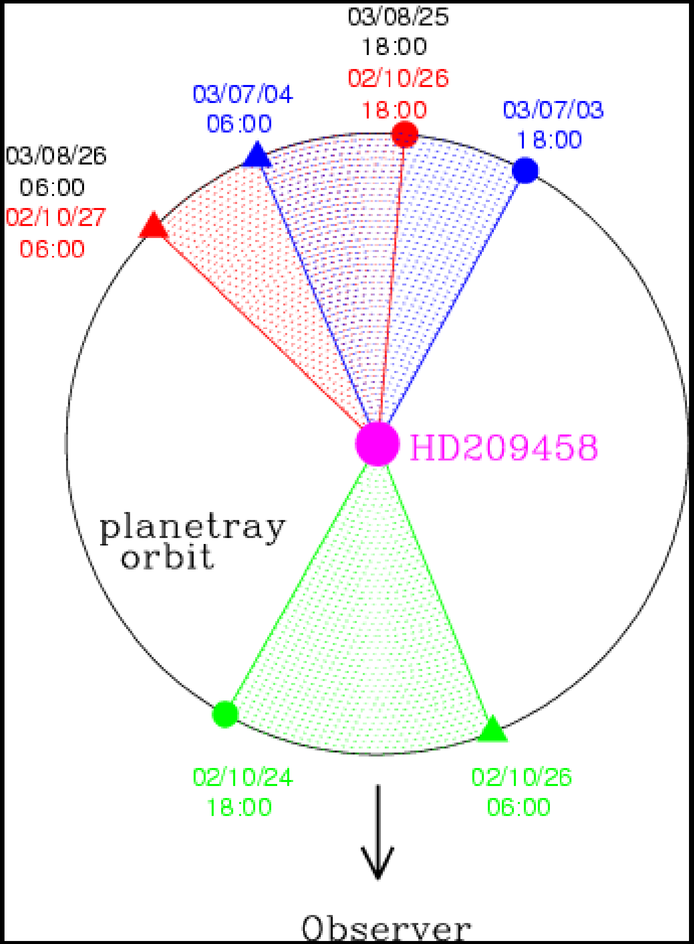
Josh Winn (Harvard Univ.)

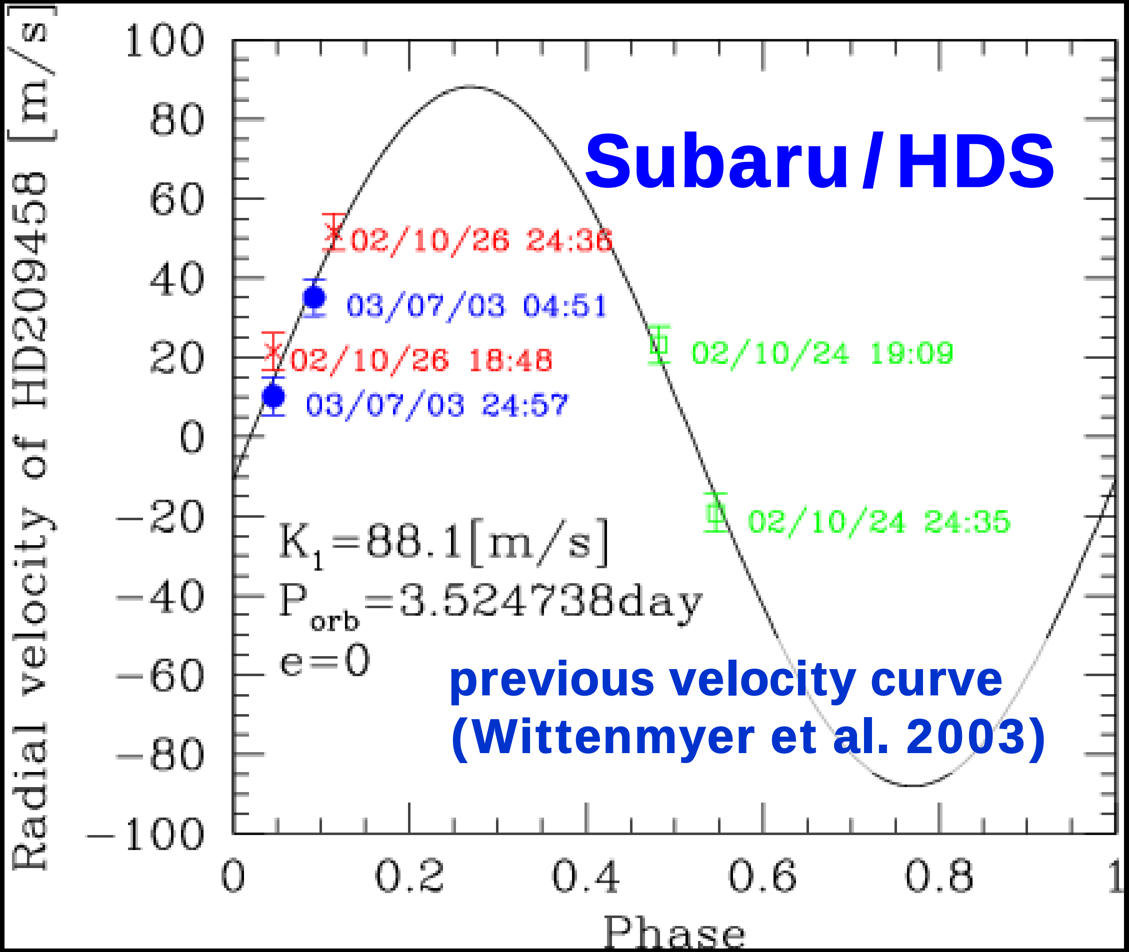
Search for scattered light from HD209458b



- 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 ($\lambda/\Delta\lambda=5540$).

Orbital phase and radial velocity of HD209458b at our observing runs

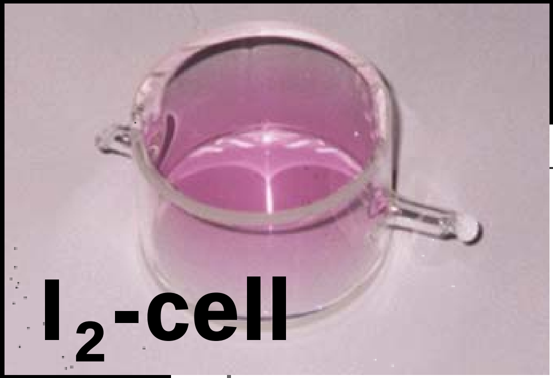


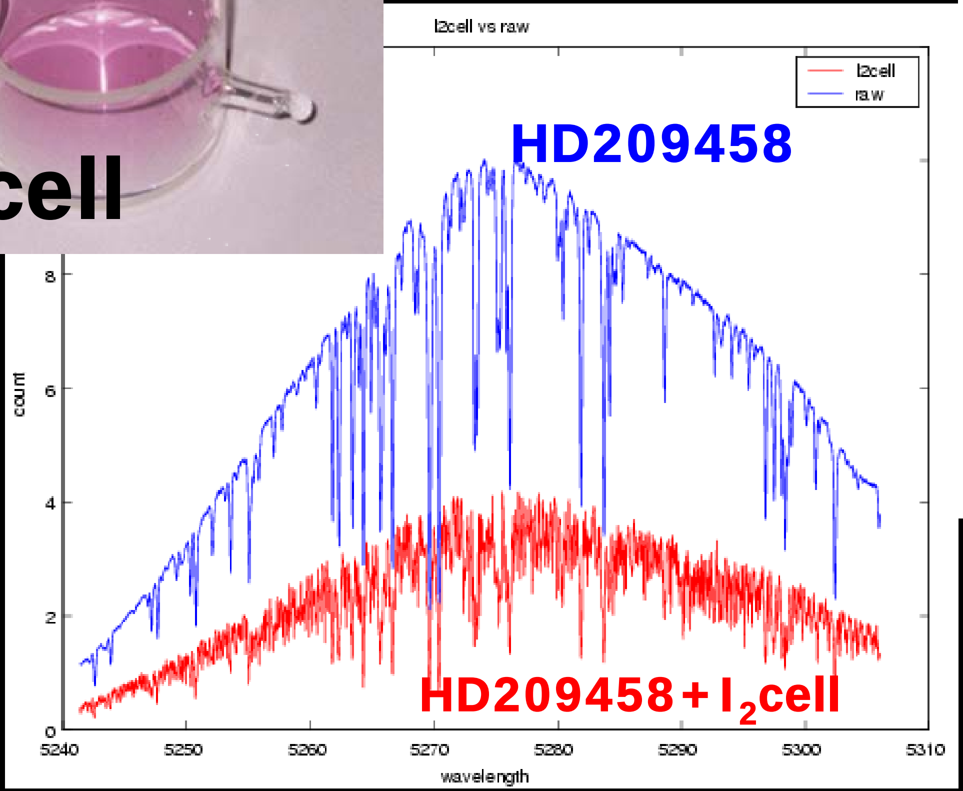


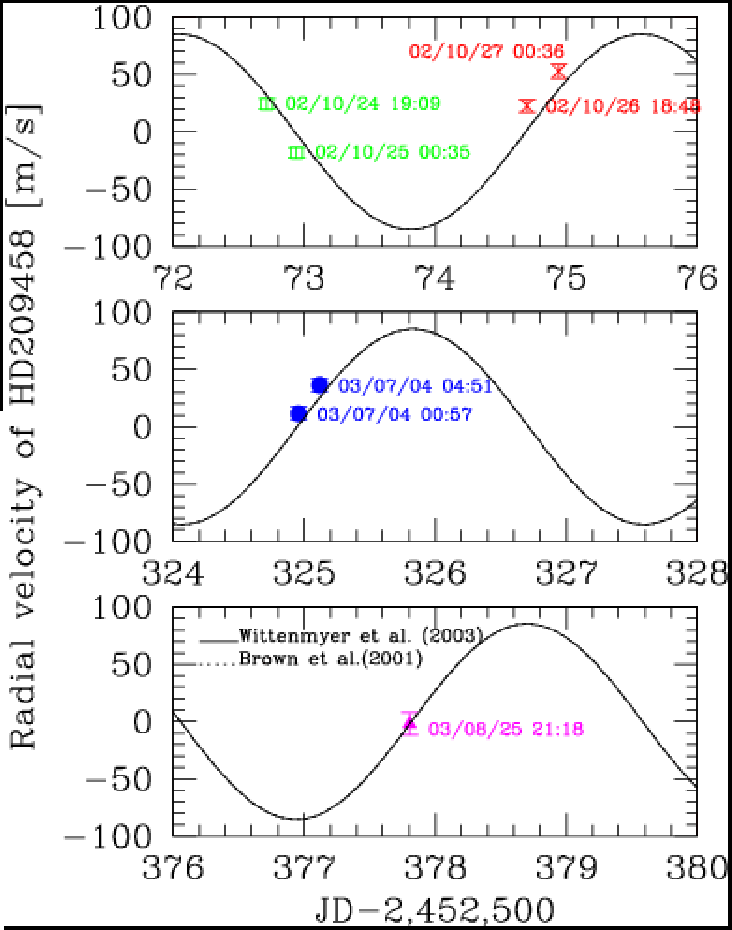
Winn et al. PASJ 56(2004) 655, astro-ph/0404469
Narita et al. PASJ 57(2005)471 , astro-ph/0504450

radial velocity measurement with I_2-cell

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



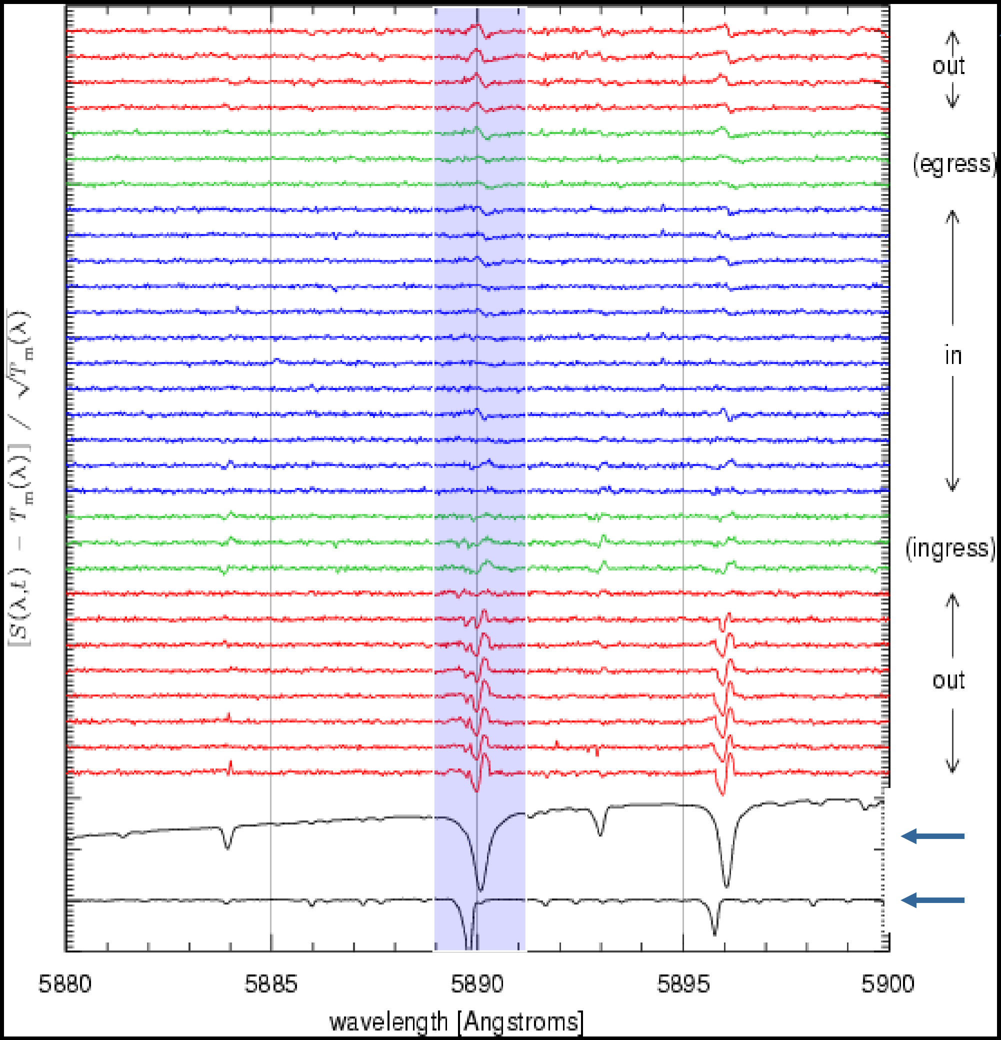


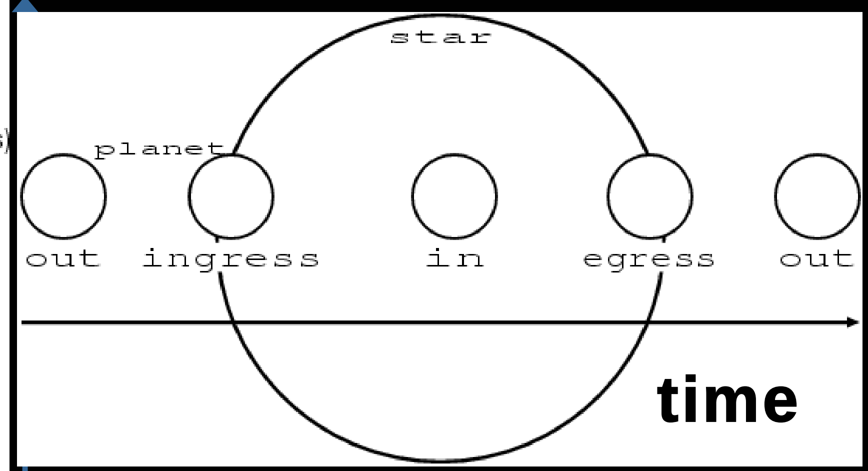


HDS on Subaru

Winn et al. (2004)

Transit transmission spectroscopy





planetary orbital phase

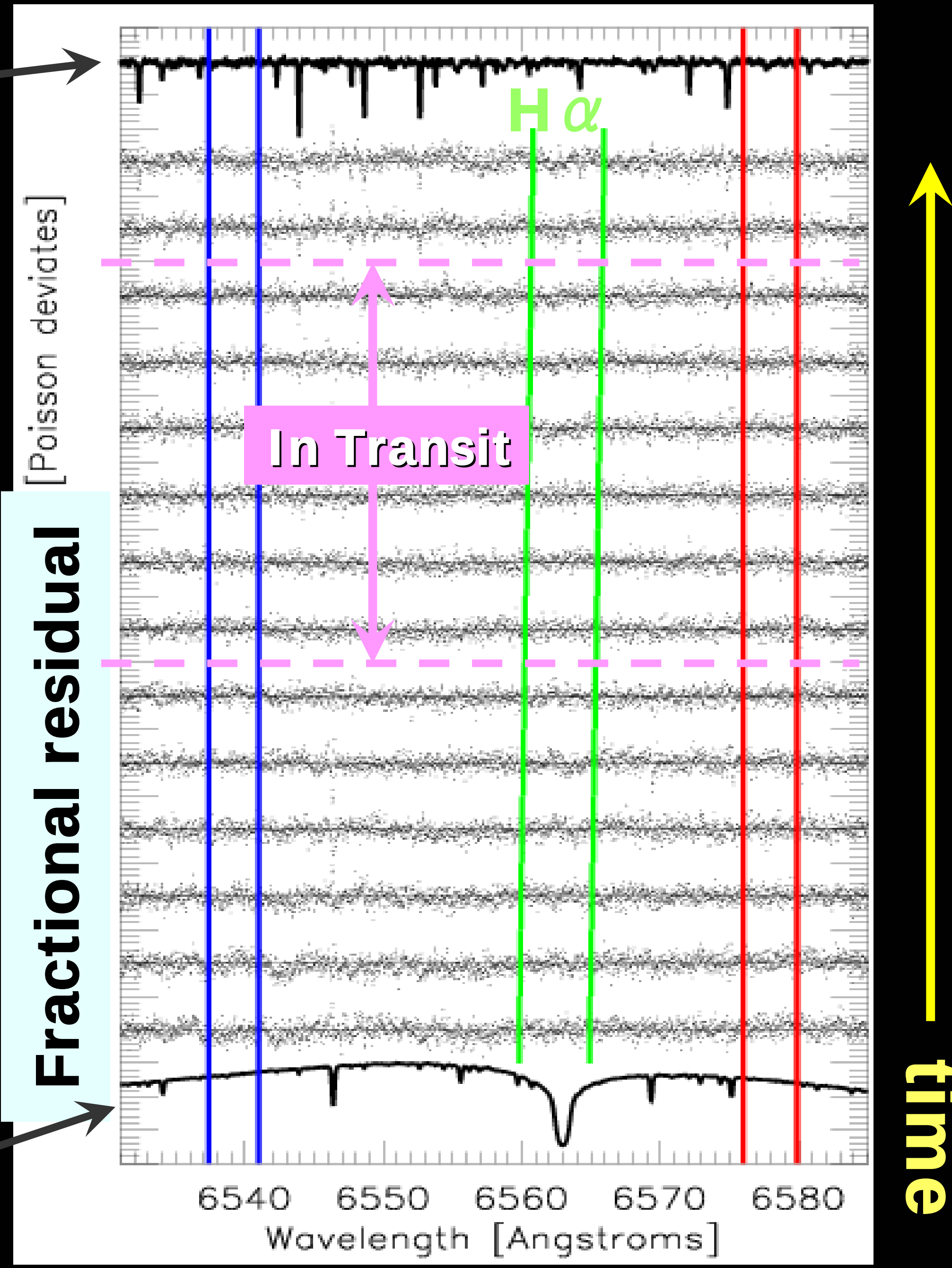
template

telluric

Narita et al. (2005)

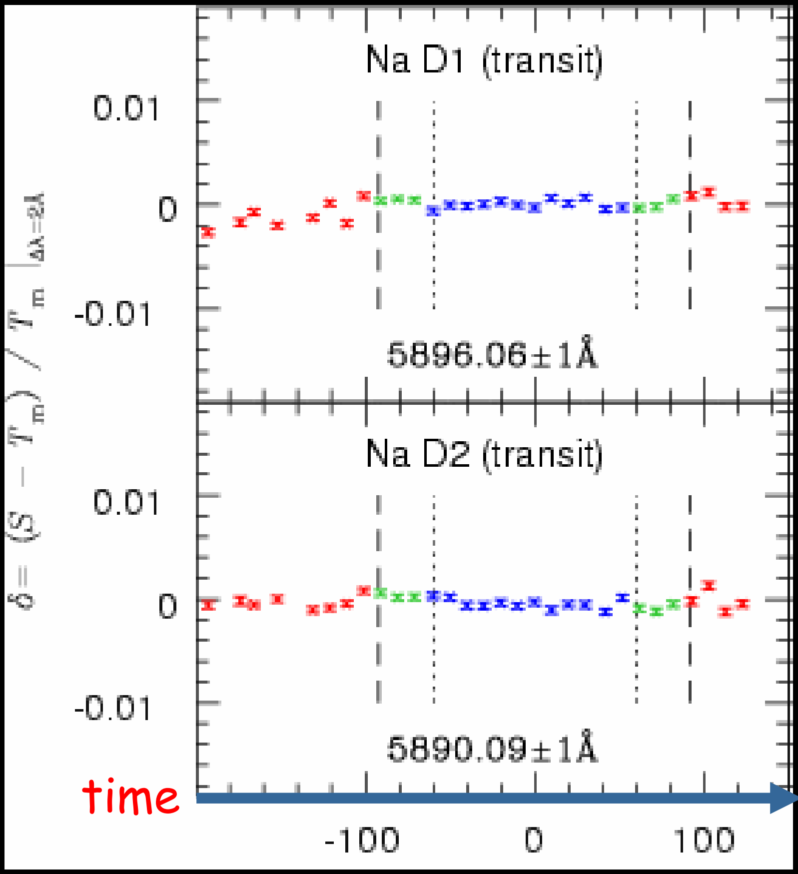
Search for H α absorption due to the atmosphere of HD209458b

Na I (D2)	5889.97 Å
Na I (D1)	5895.94 Å
H α	6562.81 Å
H β	4861.34 Å
H γ	4340.48 Å

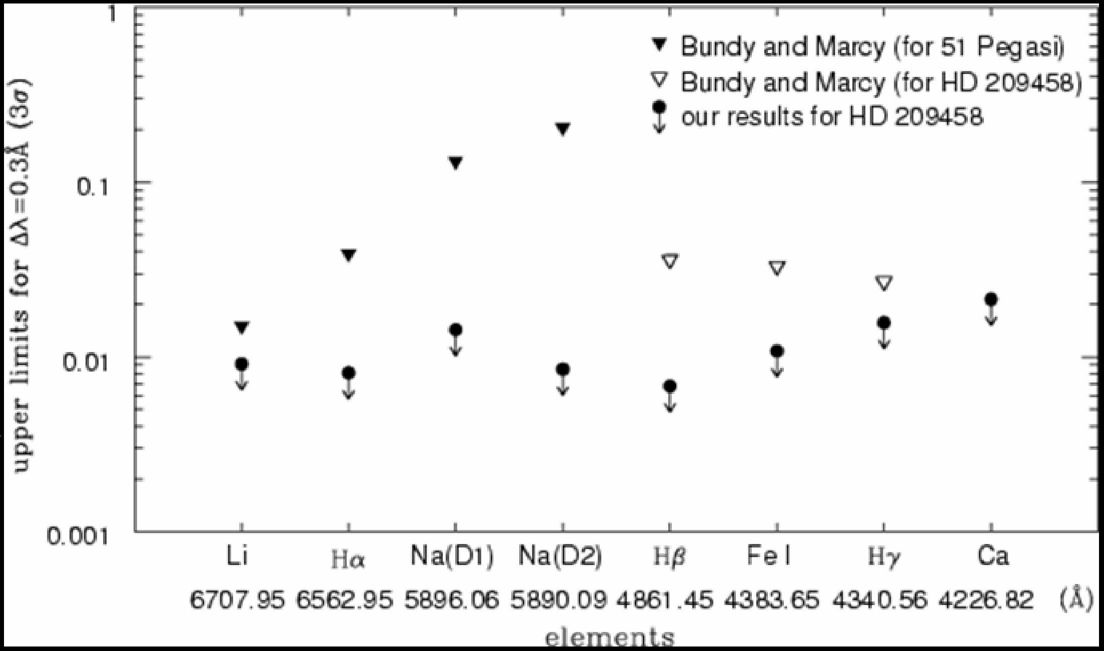


Winn et al. (2004)

most stringent upper limits from ground-based optical observations

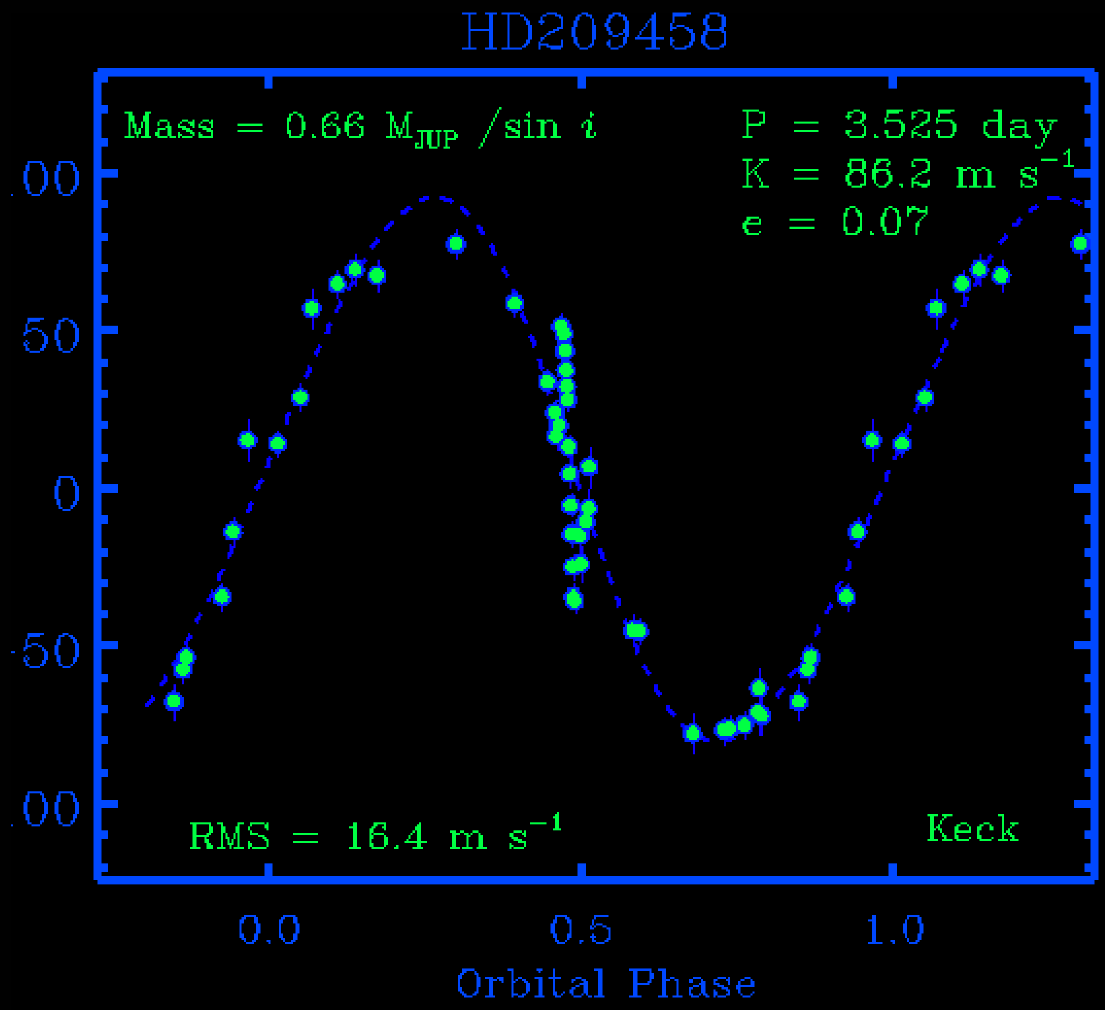


Comparison with previous results for 0.3 angstrom bandwidth (Bundy and Marcy 2000)

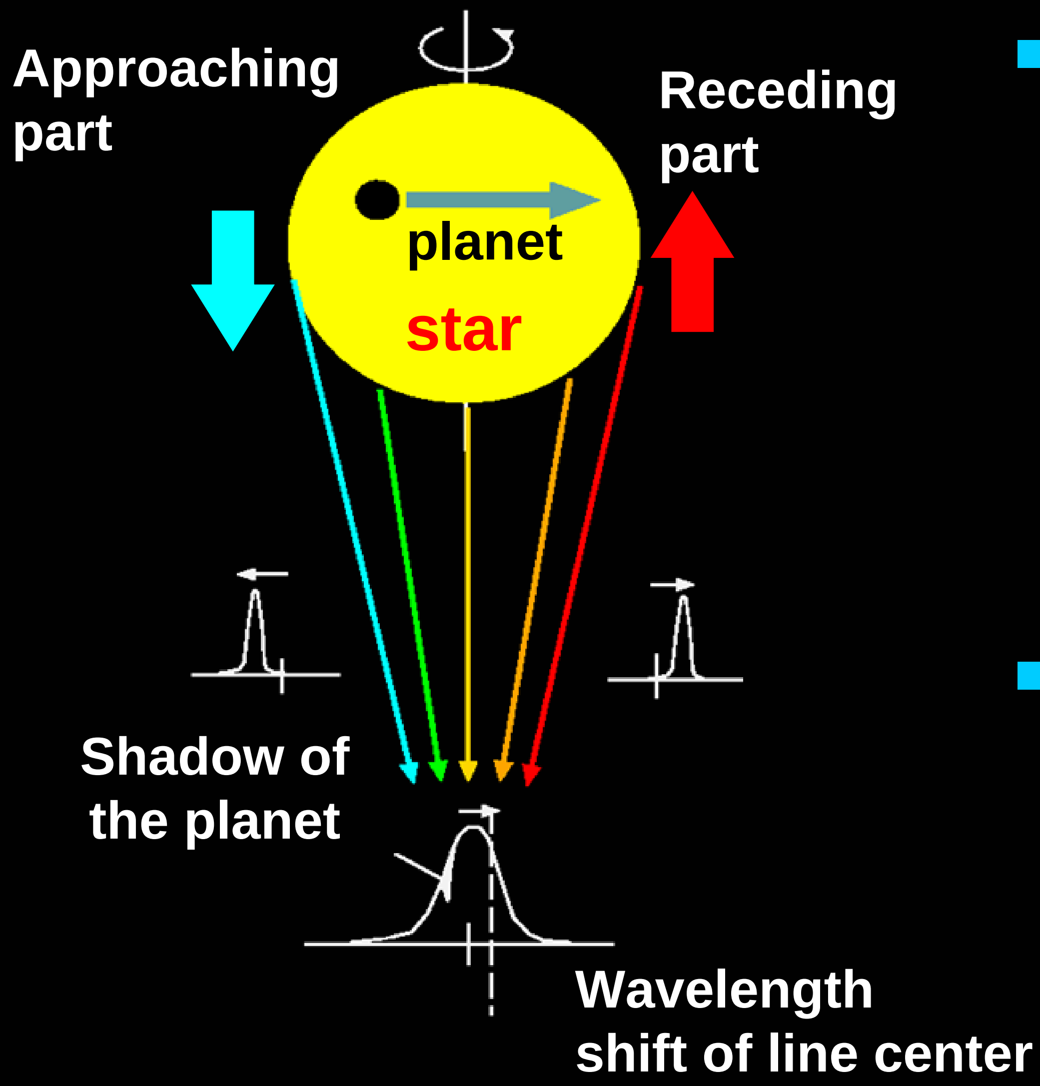


Narita et al. (2005)

Ⅳ the Rossiter effect

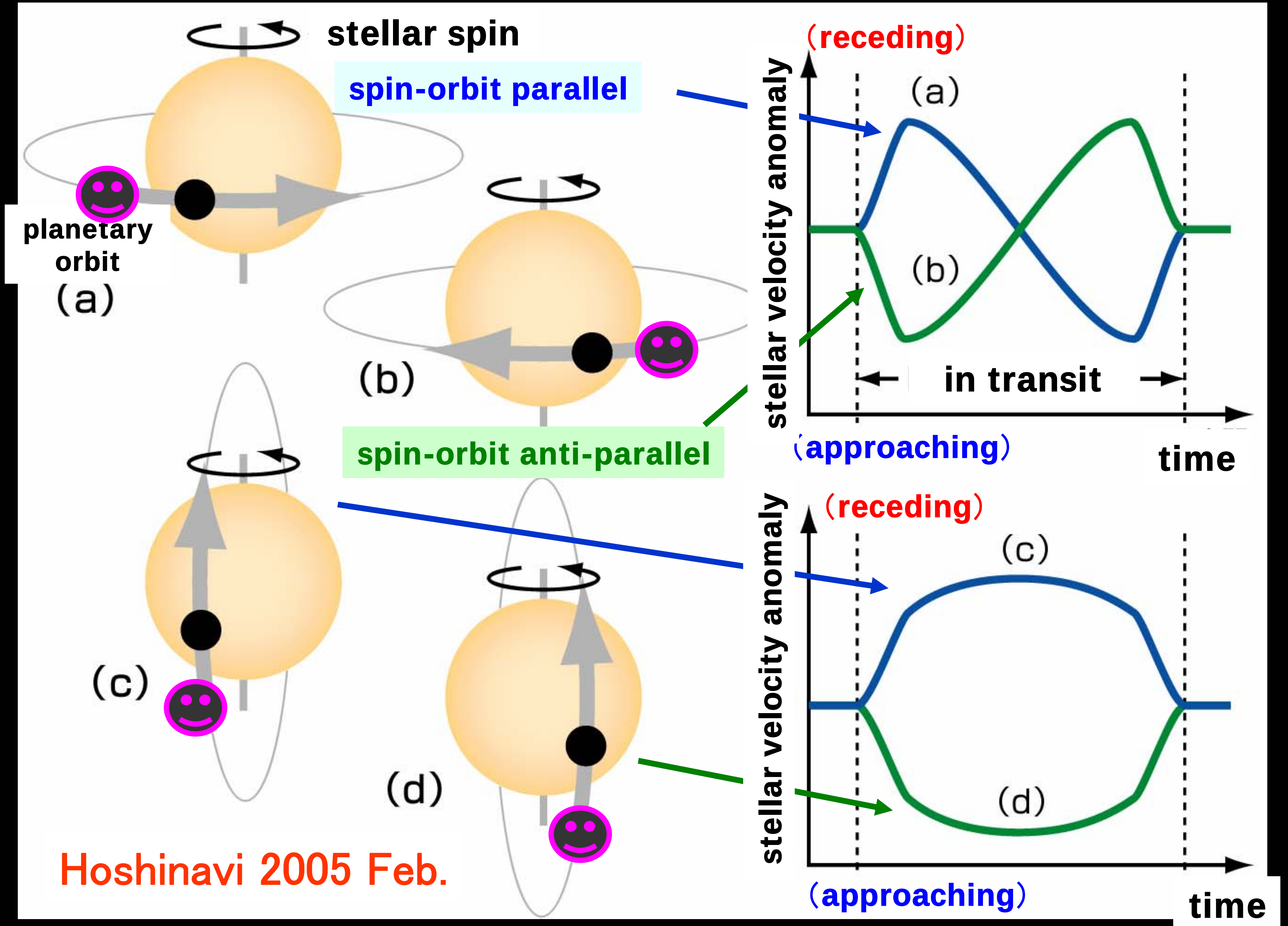


Spectroscopic transit signature: the Rossiter-McLaughlin effect



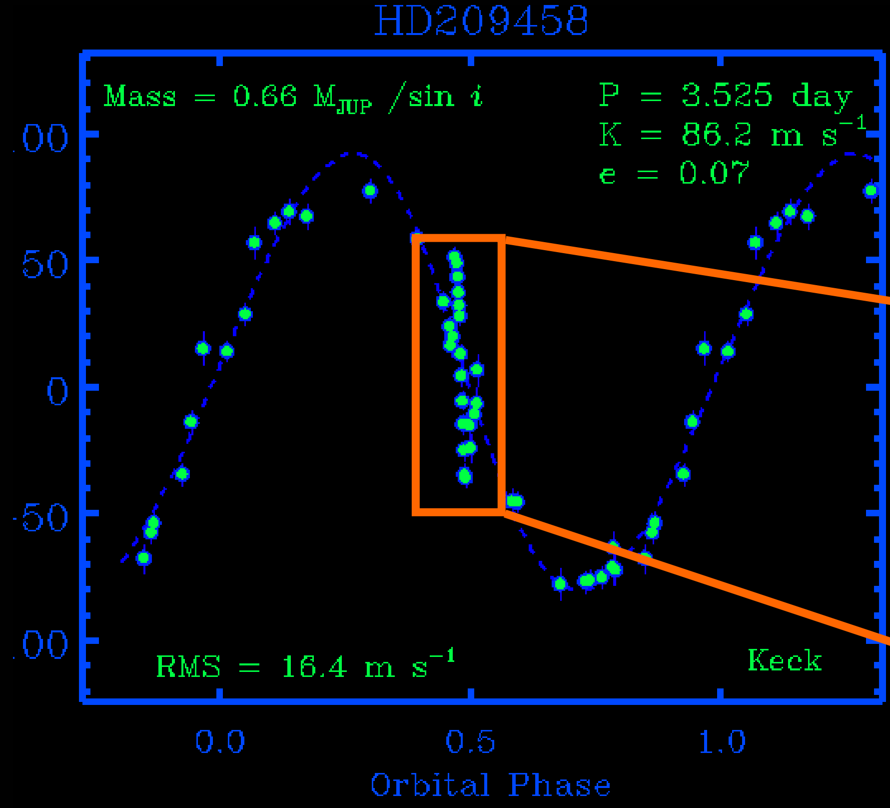
- Time-dependent asymmetry in the stellar Doppler broadened line profile
  - an apparent anomaly of the stellar radial velocity
- originally discussed in eclipsing binary systems
  - Rossiter (1924)
  - McLaughlin (1924)

Velocity anomaly due to the Rossiter effect

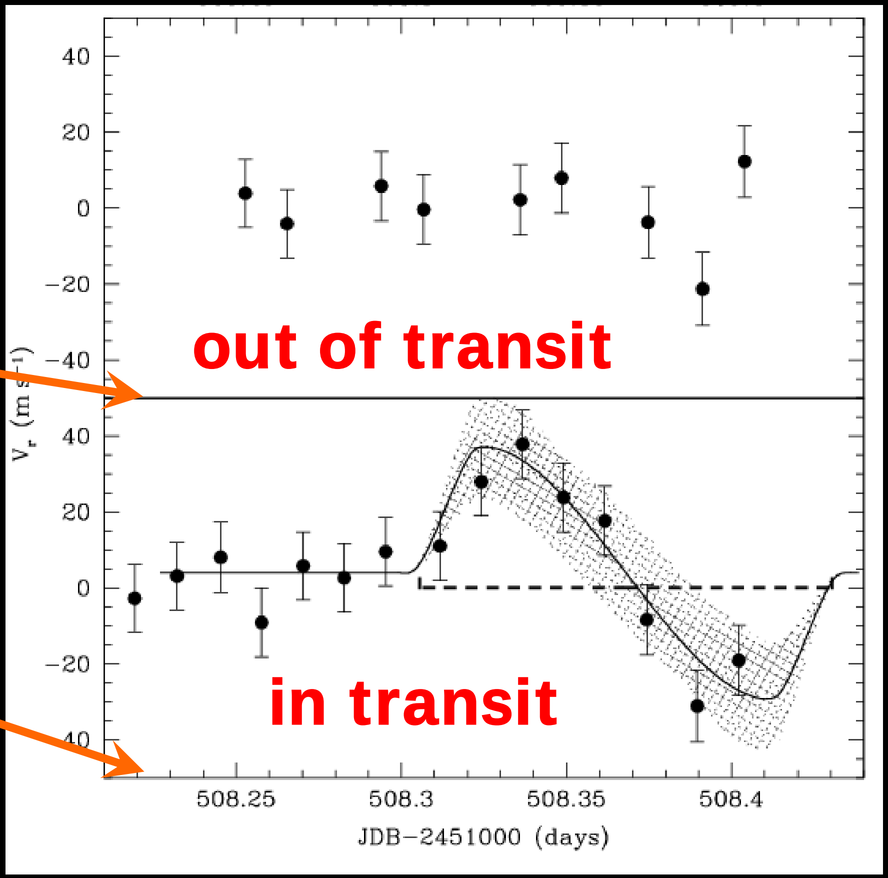


Previous result of the Rossiter-McLaughlin effect for HD209458

Origin of angular momentum



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



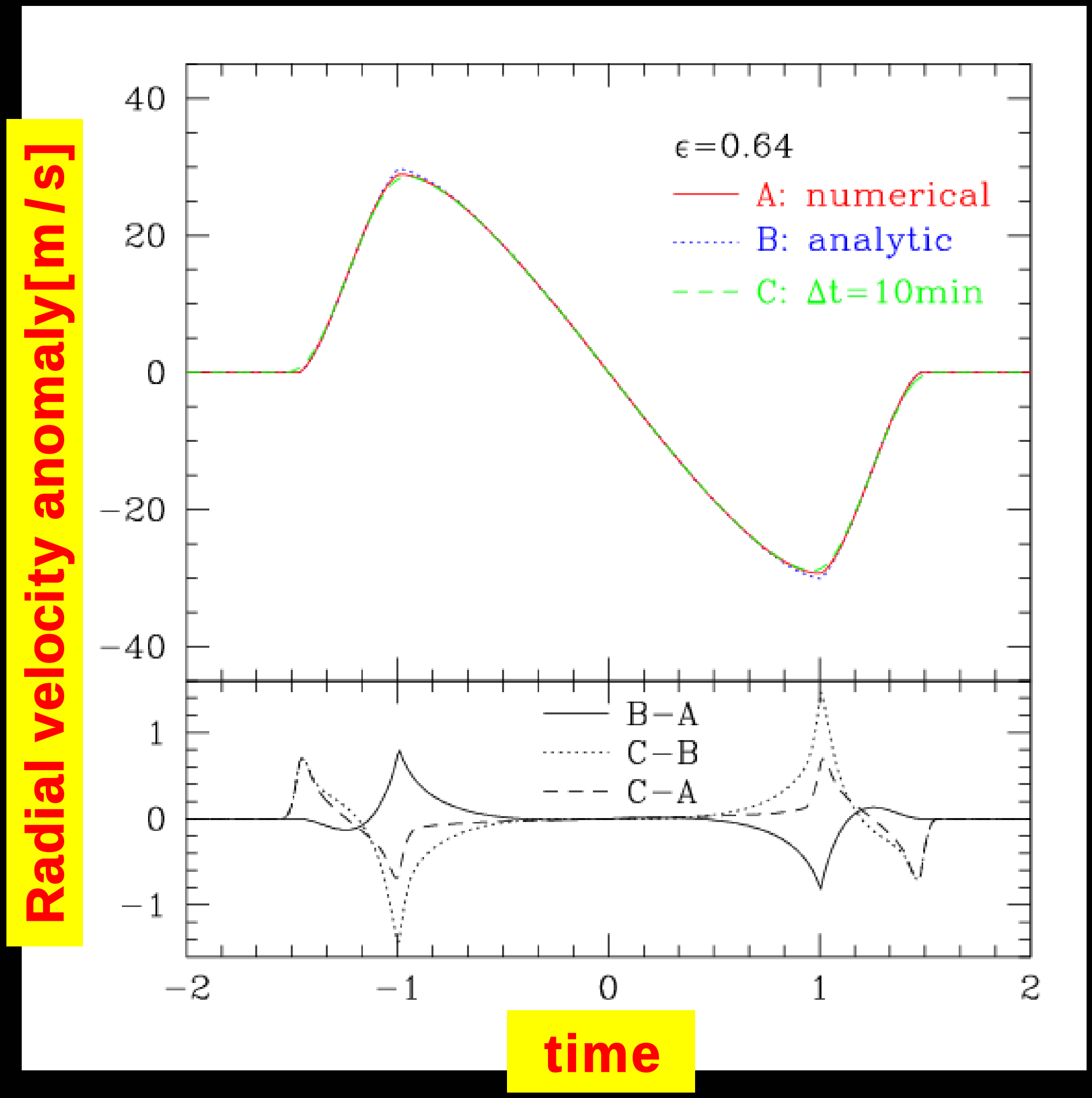
Stellar rotation and planetary orbit
Queloz et al. (2000) A&A 359, L13
ELODIE on 193cm telescope

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

Limb darkening:
B= 1- ε (1-cos θ)

First analytic formula using perturbation theory

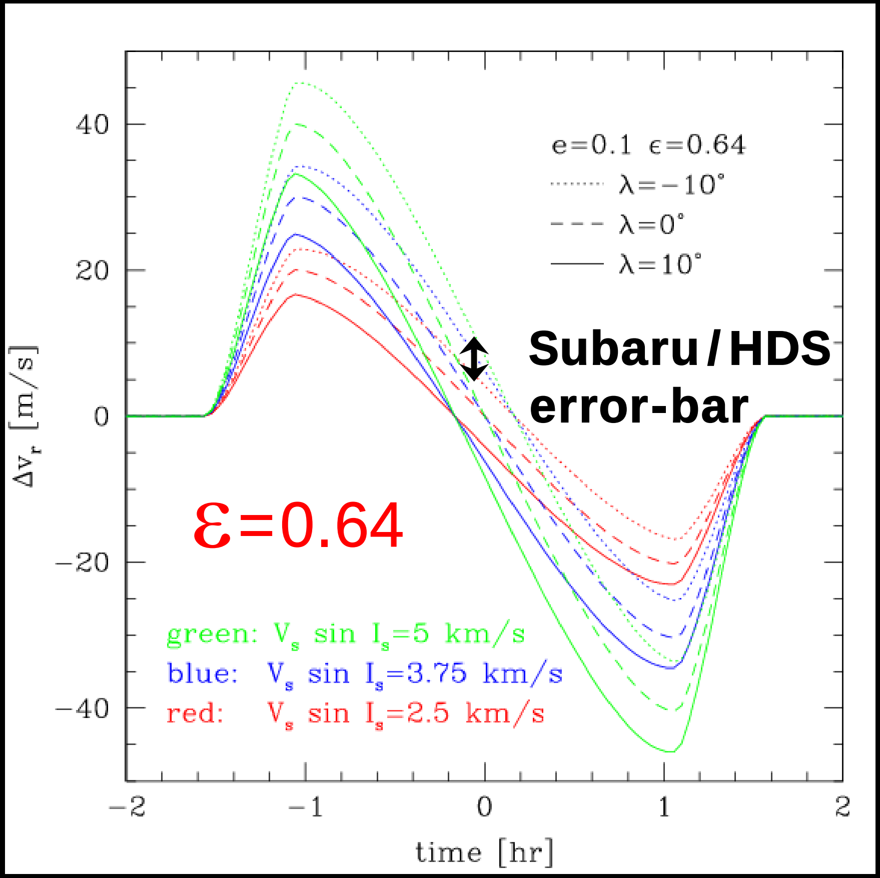
Ohta, Taruya & Suto: ApJ 622(2005)1118

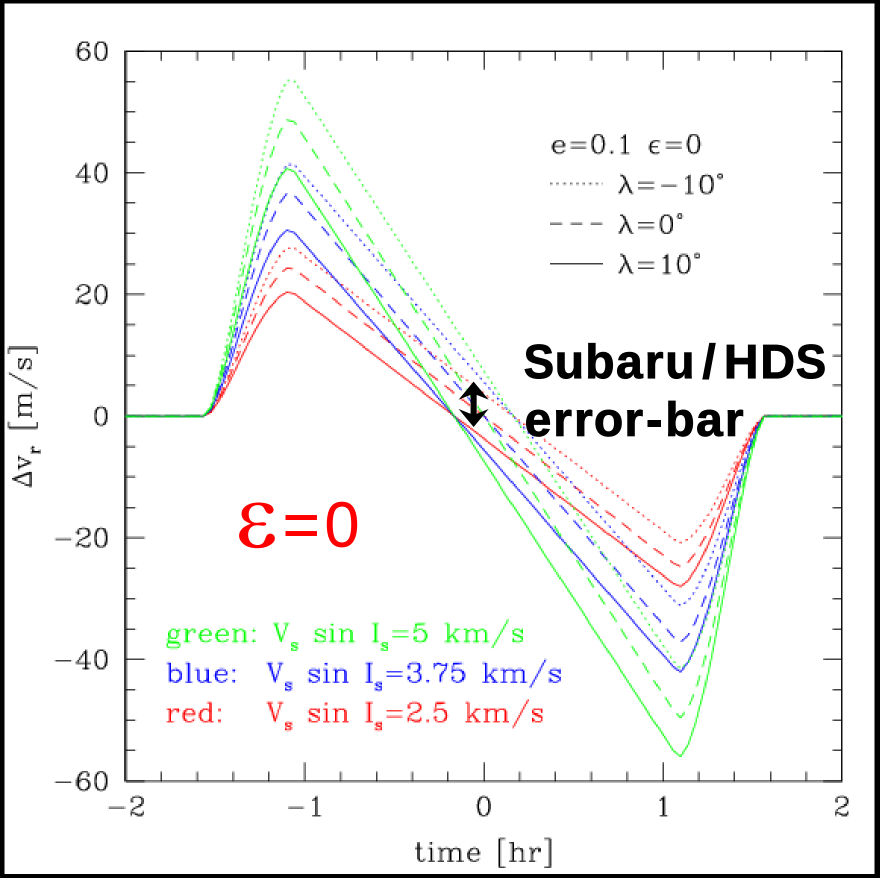


Measurement of Spin-Orbit alignment in an Extrasolar Planetary System

- **Joshua N. Winn (MIT)**, R.W. Noyes, M.J. Holman, D.B. Charbonneau, Y. Ohta, A. Taruya, Y. Suto, N. Narita, E.L. Turner, J.A. Johnson, G.W. Marcy, R.P. Butler, & S.S. Vogt
  - ApJ 631(2005)1215 (astro-ph/0504555)

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



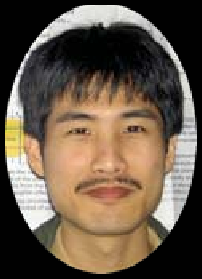


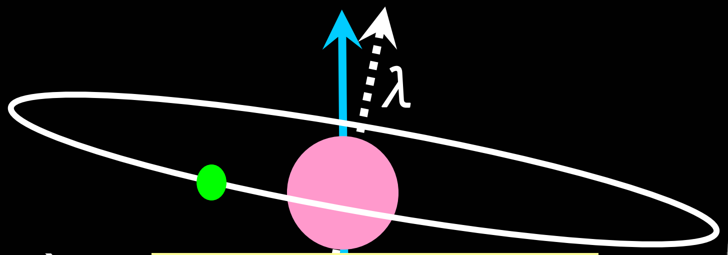
Limb darkening: B= 1- ε (1-cos θ)

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

Precision analysis of the Rossiter-McLaughlin effect for HD209458

- perturbation formula by Ohta et al. (2005)
- HD209458 re-examined with the latest data
  - radial velocity data (Keck)
  - optical photometry (HST)
  - infrared photometry (Spitzer)



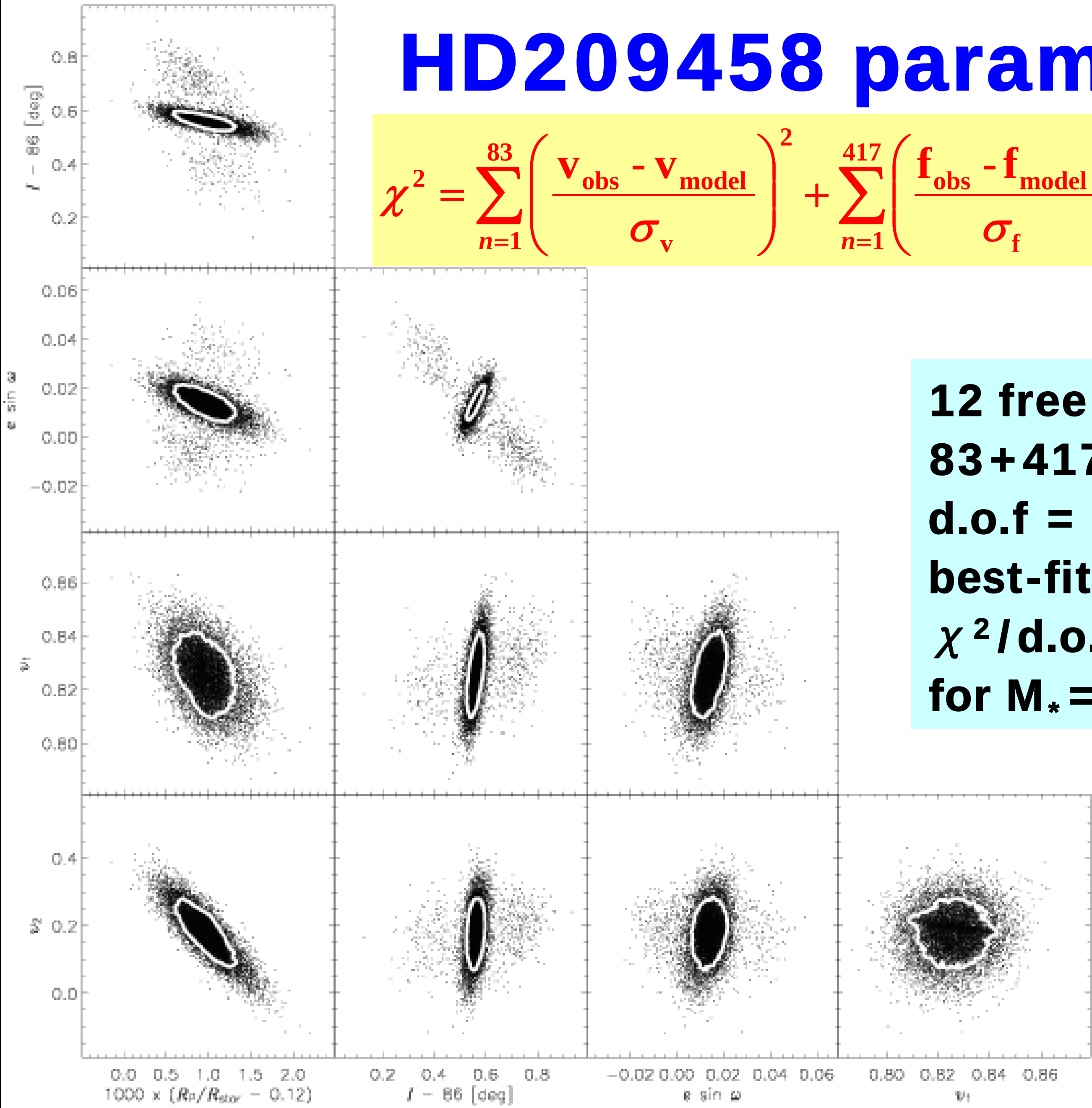


$\lambda = -4^{\circ}.4 \pm 1^{\circ}.4$

- **the first detection of the misalignment between the stellar spin and the planetary orbital axes by (−4.4±1.4)deg**
  - an order-of-magnitude more accurate than before
  - c.f., 6 degree misalignment for the Solar system
- **$\lambda \neq 0$ problem other than in cosmology !**

HD209458 parameter fit

$$\chi^2 = \sum_{n=1}^{83}\left(\frac{v_{obs} - v_{model}}{\sigma_v}\right)^2 + \sum_{n=1}^{417}\left(\frac{f_{obs} - f_{model}}{\sigma_f}\right)^2 + \left(\frac{t_{2nd,obs} - t_{2nd,model}}{\sigma_t}\right)^2$$



12 free parameters

83+417+1 data points

d.o.f = 83+417+1-12=489

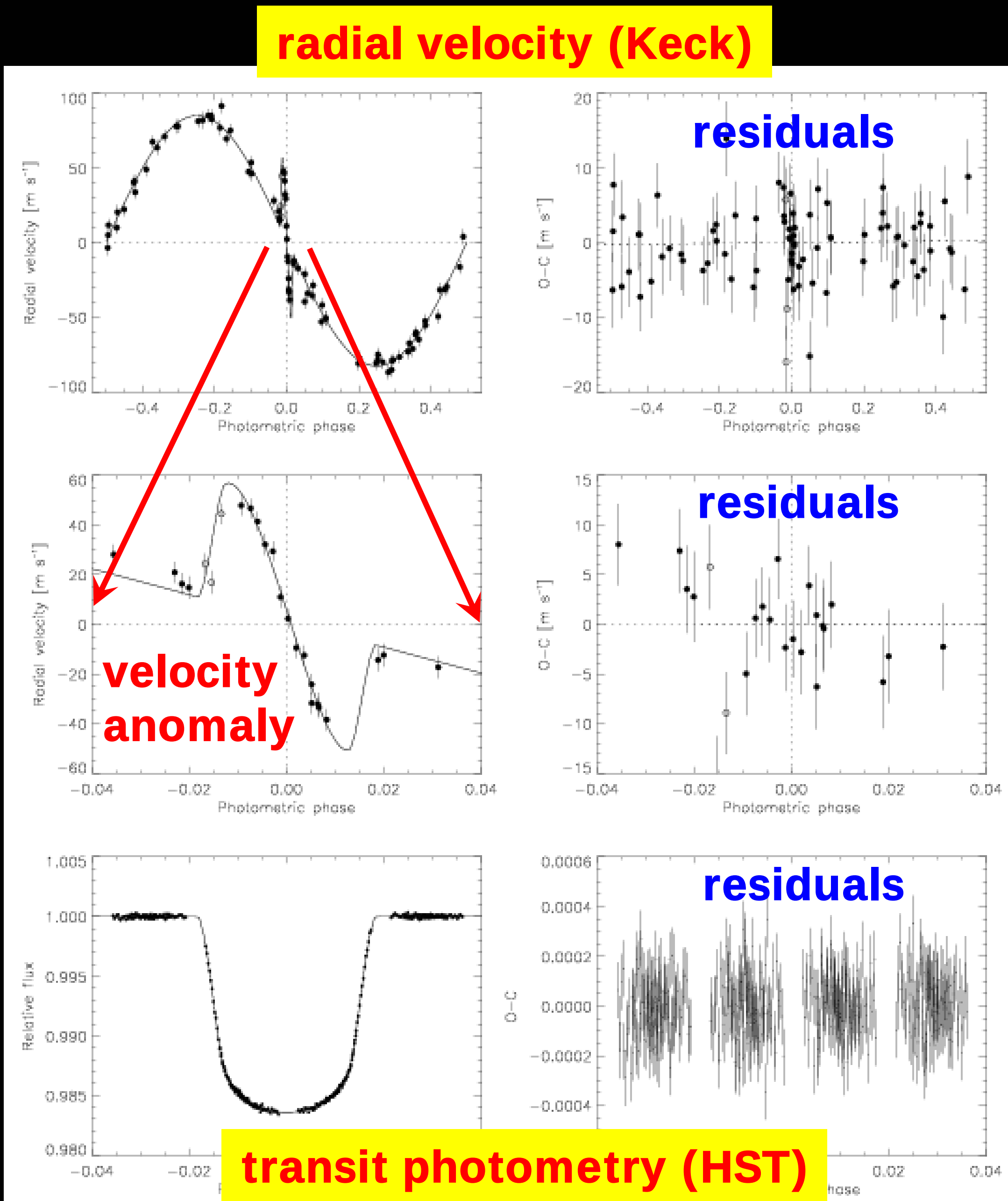
best-fit :

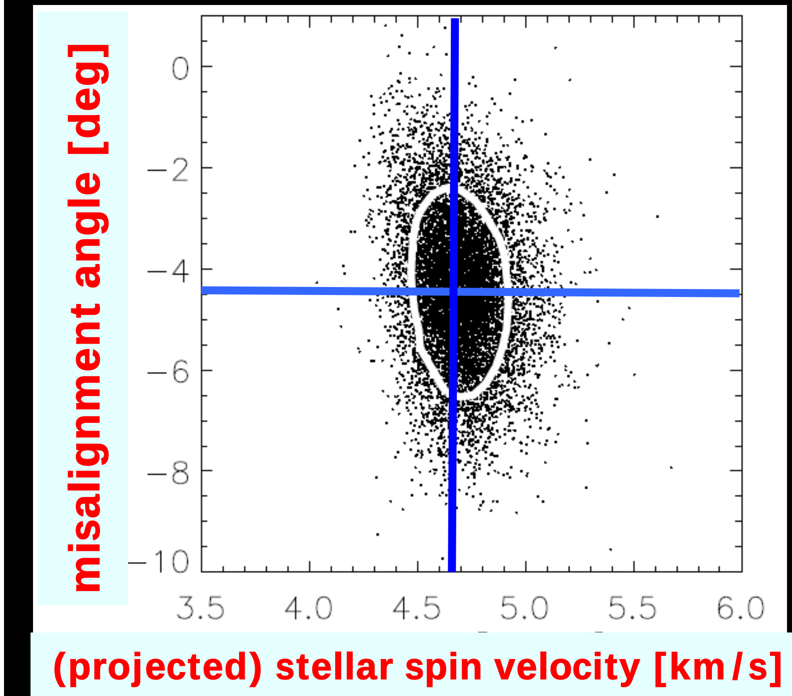
χ^2/d.o.f=528/489=1.08

for $M_*=1.06M_{sun}$

Winn et al.
astro-ph/0504555
ApJ 631(2005)1215

first detection of non-zero λ !





$$\lambda = -4^{\circ}.4 \pm 1^{\circ}.4$$

3 σ detection !

Winn et al. astro-ph/0504555 ApJ 631(2005)1215

Our group detected the Rossiter effect for 4 transiting planets so far

- HD209458b (Winn et al. 2005) λ = -4.4±1.4deg
- HD189733b (Winn et al. 2006) λ = -1.4±1.1deg
- TrES-1b (Narita et al. 2006) λ = 30±21deg
- HAT-P-2b (Winn et al. 2007) λ = 0.3±9.8deg

More to come !

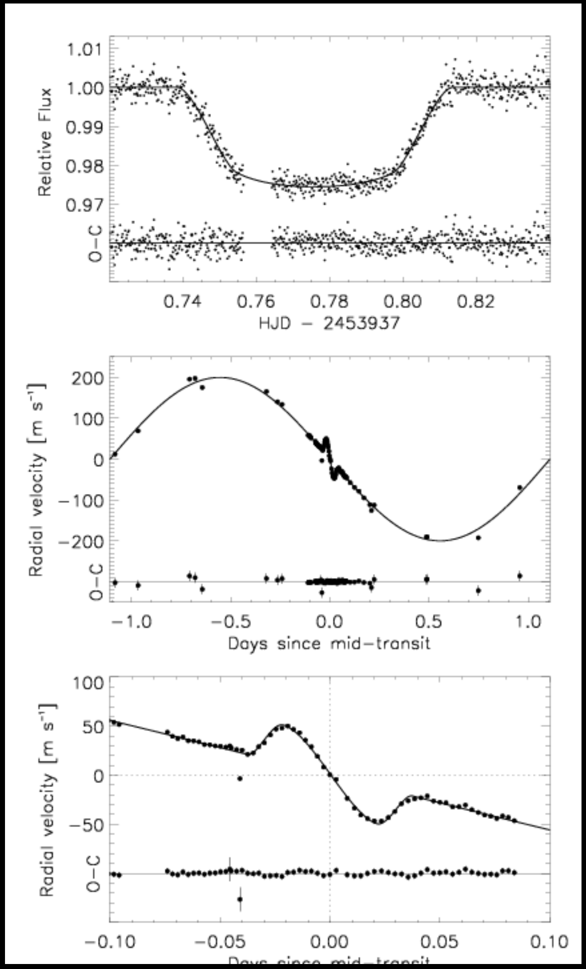
Subaru (radial velocity) & MAGNUM (photometry)

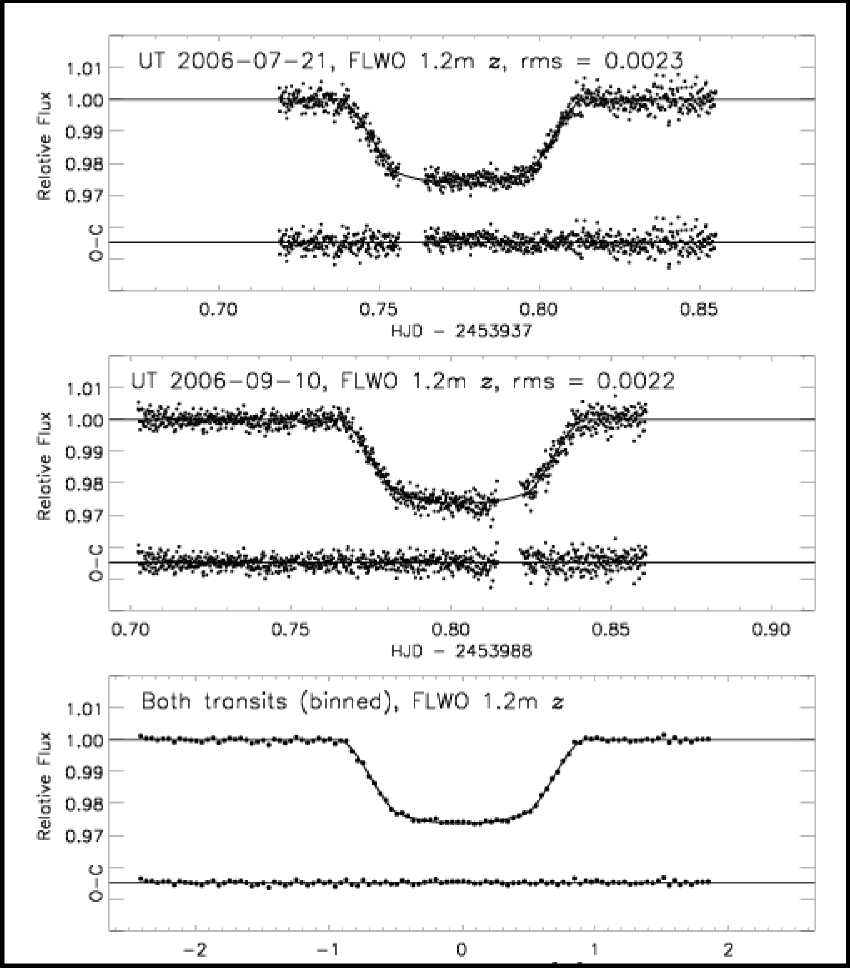
simultaneous observation campaign

P.I. N.Narita

Measurement of the Spin-Orbit Alignment in the Exoplanetary System HD 189733

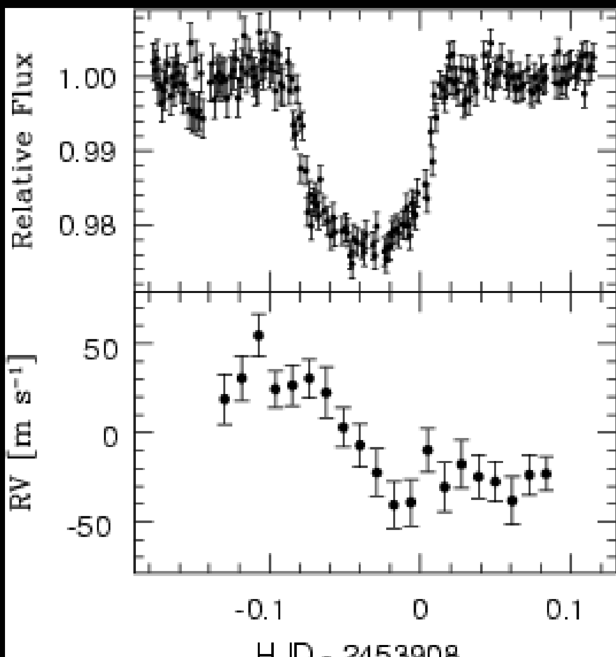
- Winn et al. ApJ 653(2006)L69, AJ 133(2007)1828

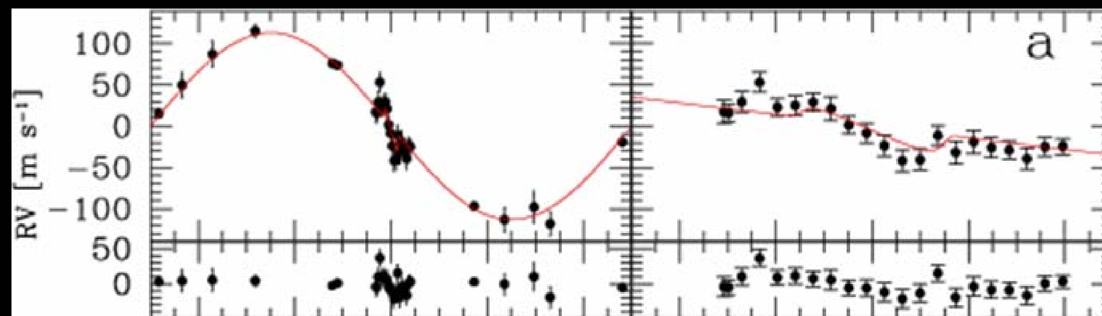


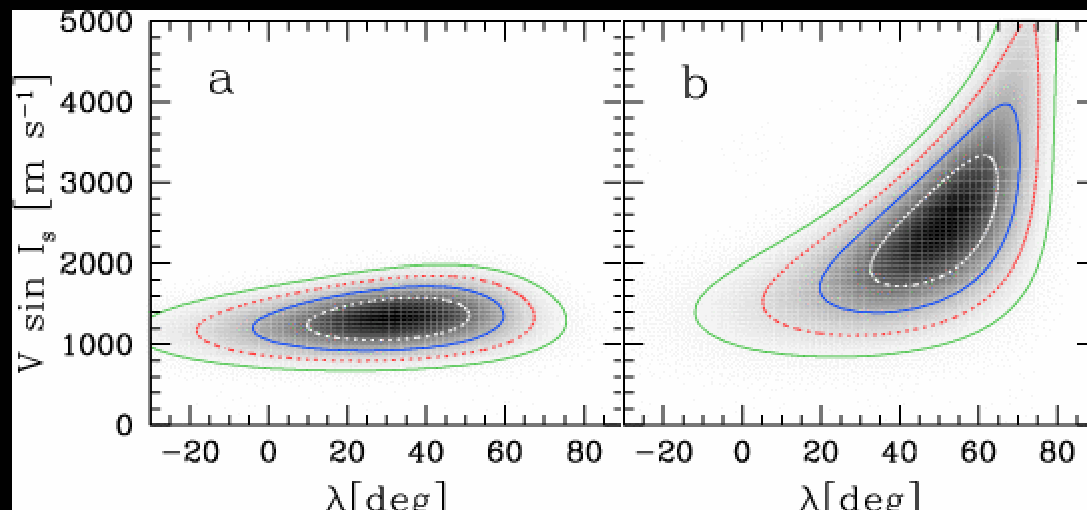


Measurement of the Rossiter-McLaughlin Effect in the Transiting Exoplanetary System TrES-1

- Narita et al. PASJ (2007) in press, astro-ph/0702707

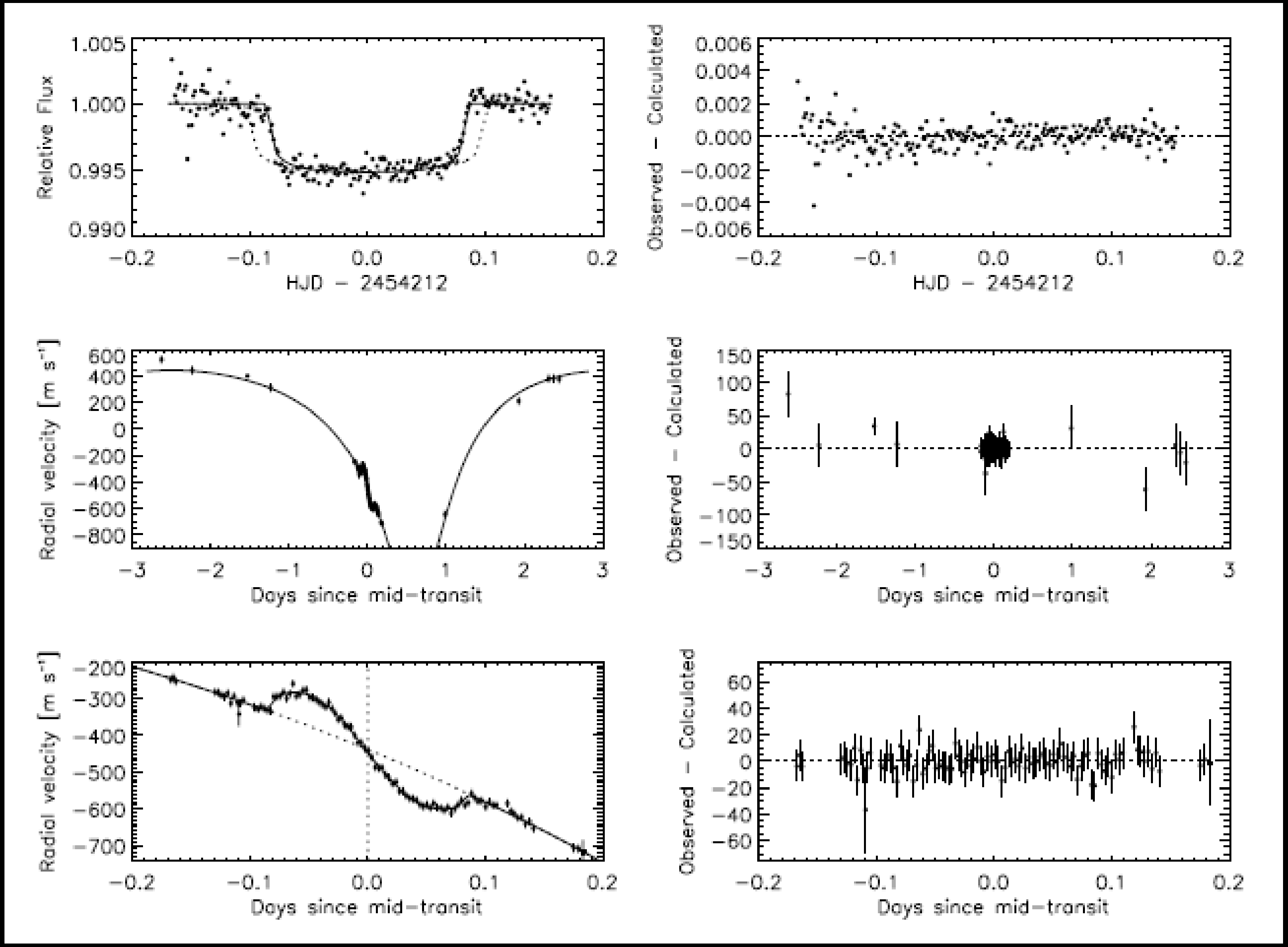






Spin-Orbit Alignment in the Exoplanetary System HAT-P-2

- Winn et al. ApJL(2007) in press



HATnet: *Hungarian-made Automated Telescope*

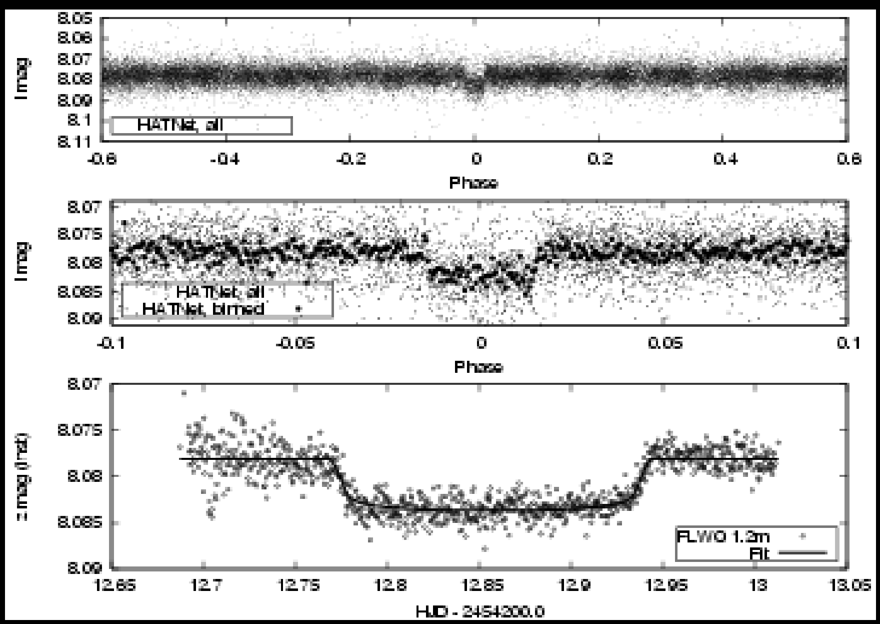
- HATNet is a network of six small (11cm diameter), wide-field (8x8deg), fully-automated "HAT" telescopes
- a multi-site and multi-instrument network searching for the tiny (1%) transit signature of extrasolar planets

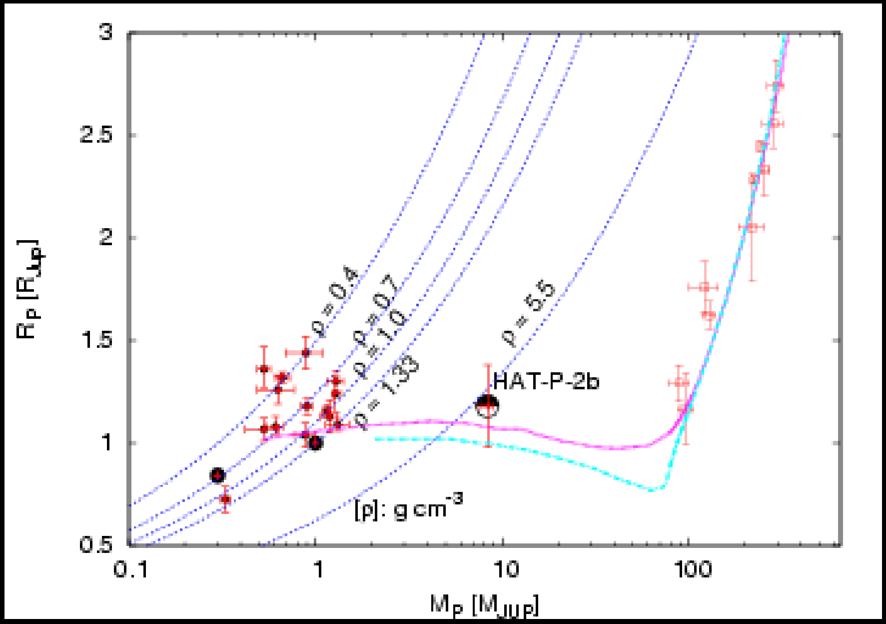

Mauna Kea, Hawaii
Fred Lawrence Whipple Obs., Arizona
Wise, Israel



HAT-P-2b: A Super-Massive Planet in an Eccentric Orbit Transiting a Bright Star

- Central star: HD147506
  - V=8.7, F8V, d=135pc, 4.3L_{sun}, 1.35M_{sun}, 1.8R_{sun}
- Planet: HD147506b=HAT-P-2b
  - P=5.63day, e=0.5, 8.2M_J, 1.2R_J, ρ =6.6g/cc

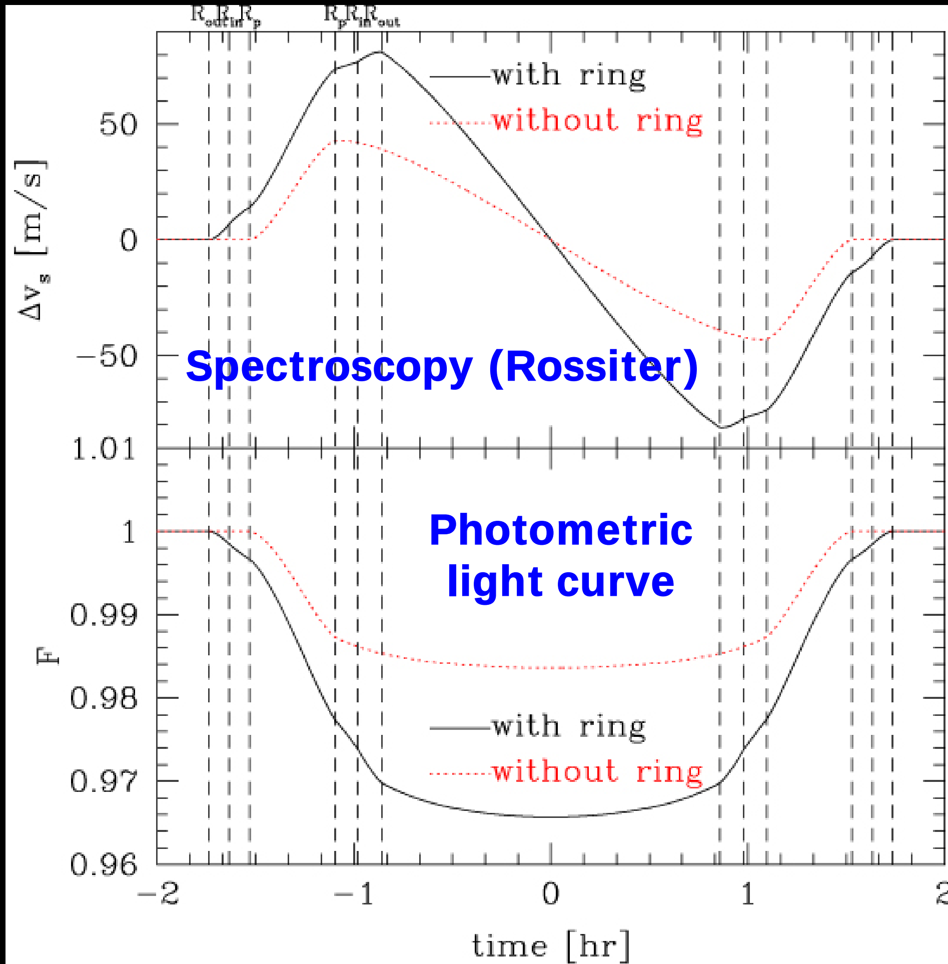


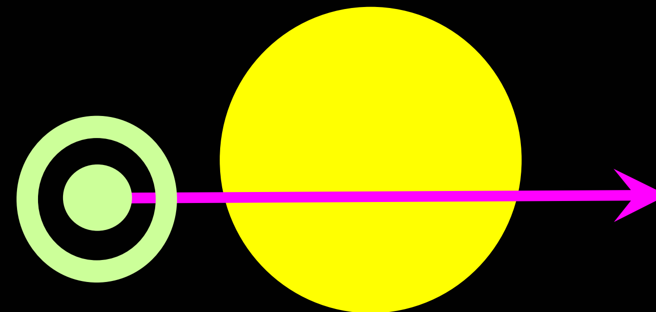


Discovery of the Uranus rings

- **Serendipitous discovery**
  - Uranus's transit against a background star (Elliot et al. 1977)
  - Neptune's ring was discovered also by transit technique in 1986
- **Transit proved to be useful in detecting rings of the Solar planets !**

Signatures of planetary rings

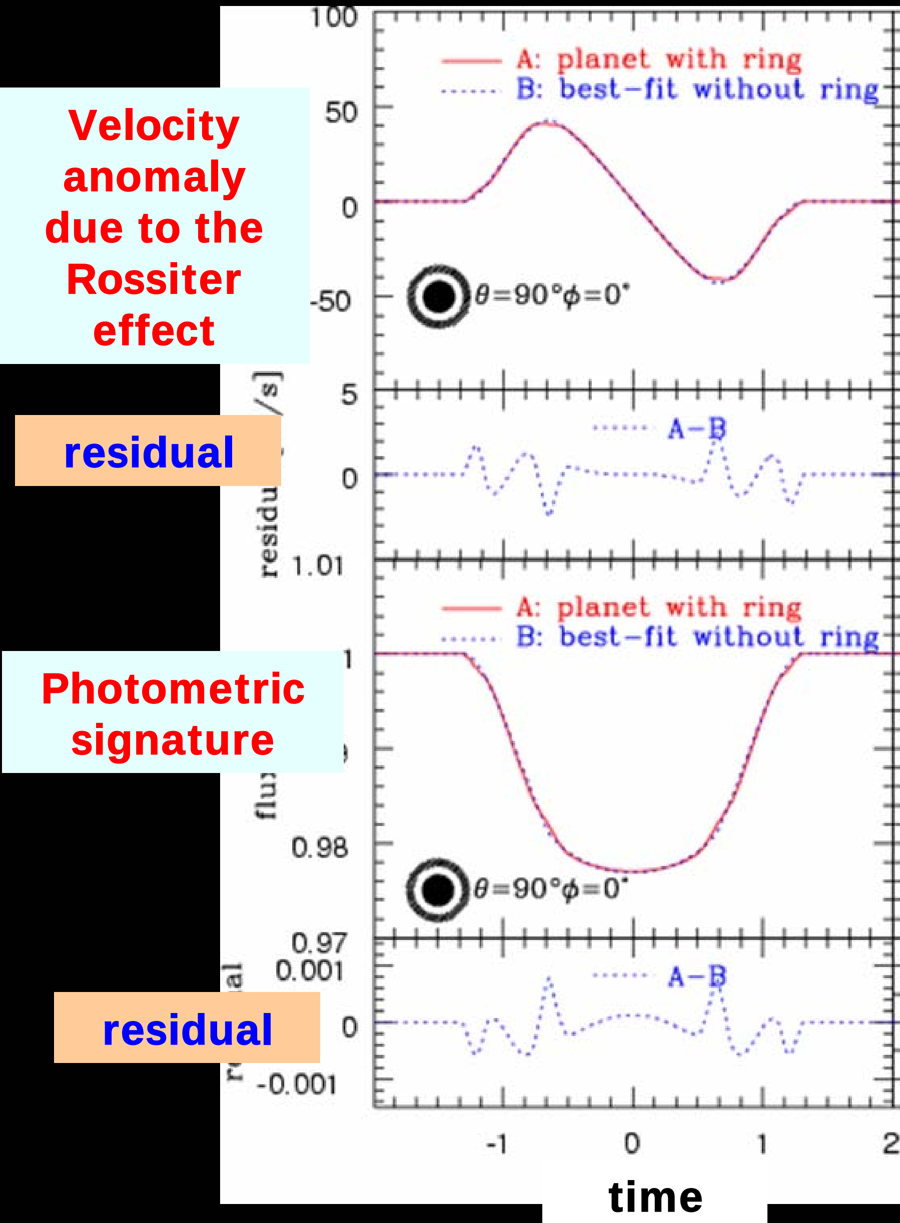




- Ring's inner and outer radii, gap, planet's radius imprints strong features in the photometric and spectroscopic data
- Statistical analysis of the residuals with respect to the best-fit ringless model

Ohta, Taruya & YS: astro-ph/0611466

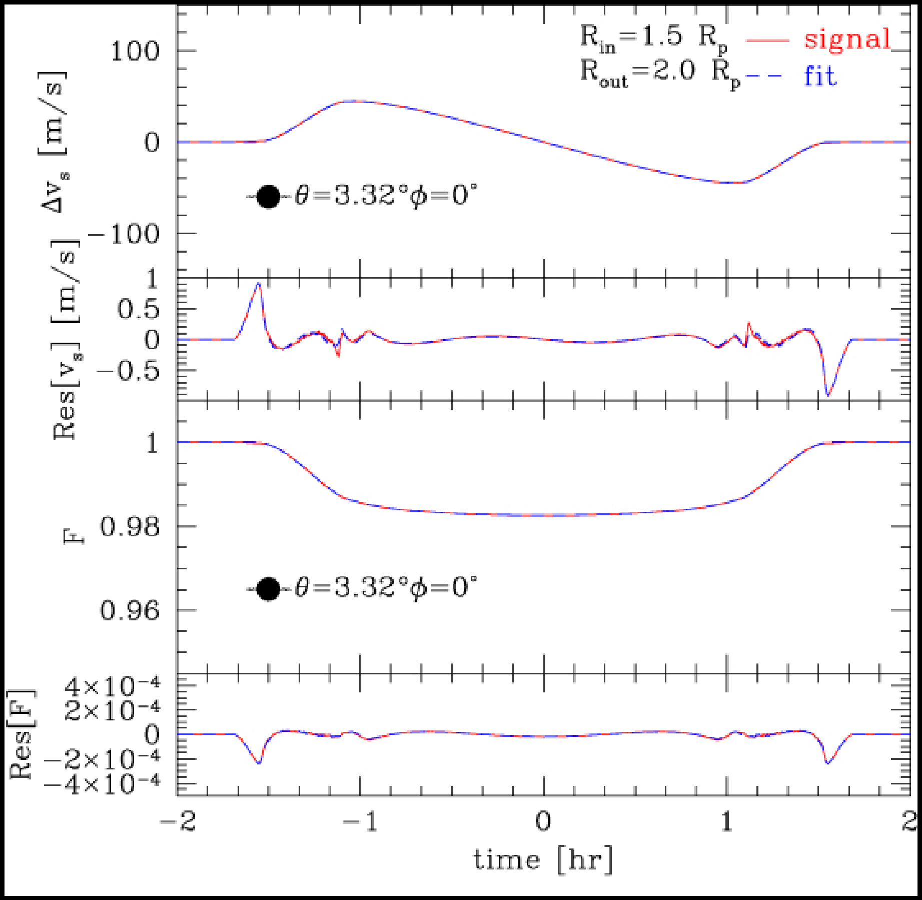
Detectability of a ring

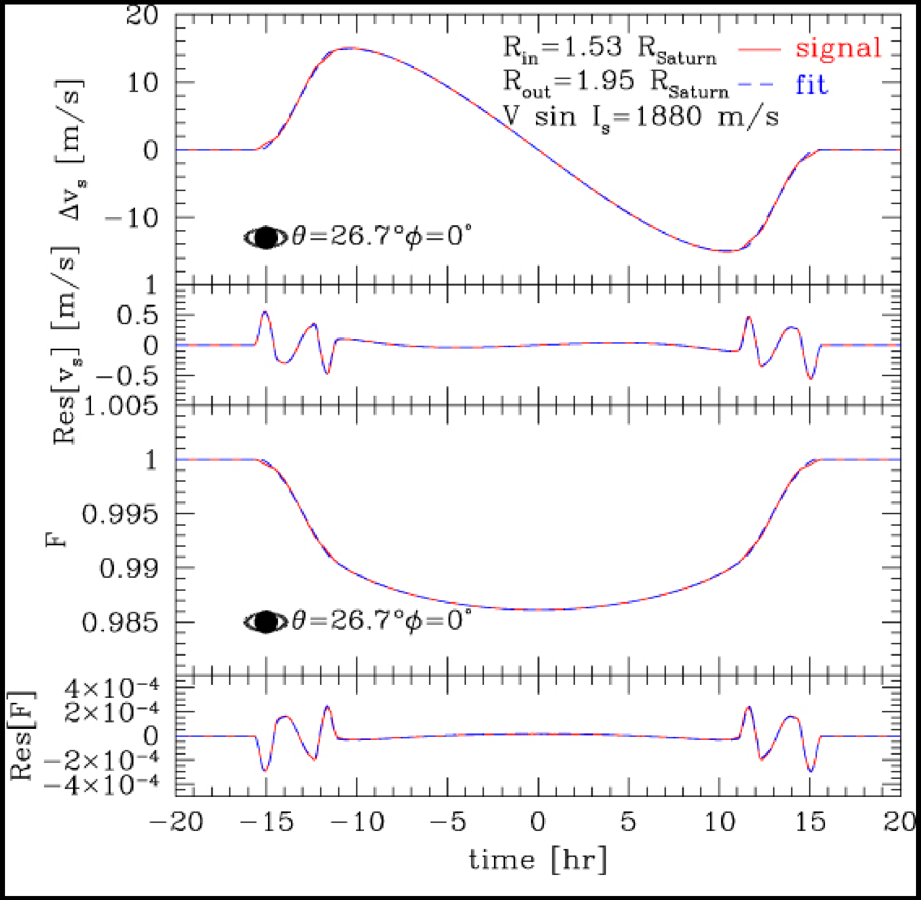


- a hypothetical ring around HD209458
  - $1.5R_{pl} < R_{ring} < 2R_{pl}$
  - deviation from a best-fit single planet
  - $\delta v \sim 1 m/s$
  - $\delta F/F \sim 0.1\%$
- marginally detectable level even with the current technology

Ohta, Taruya & YS: astro-ph/0611466

How about hot Jupiter and Saturn rings ?





Ohta, Taruya & YS: astro-ph/0611466

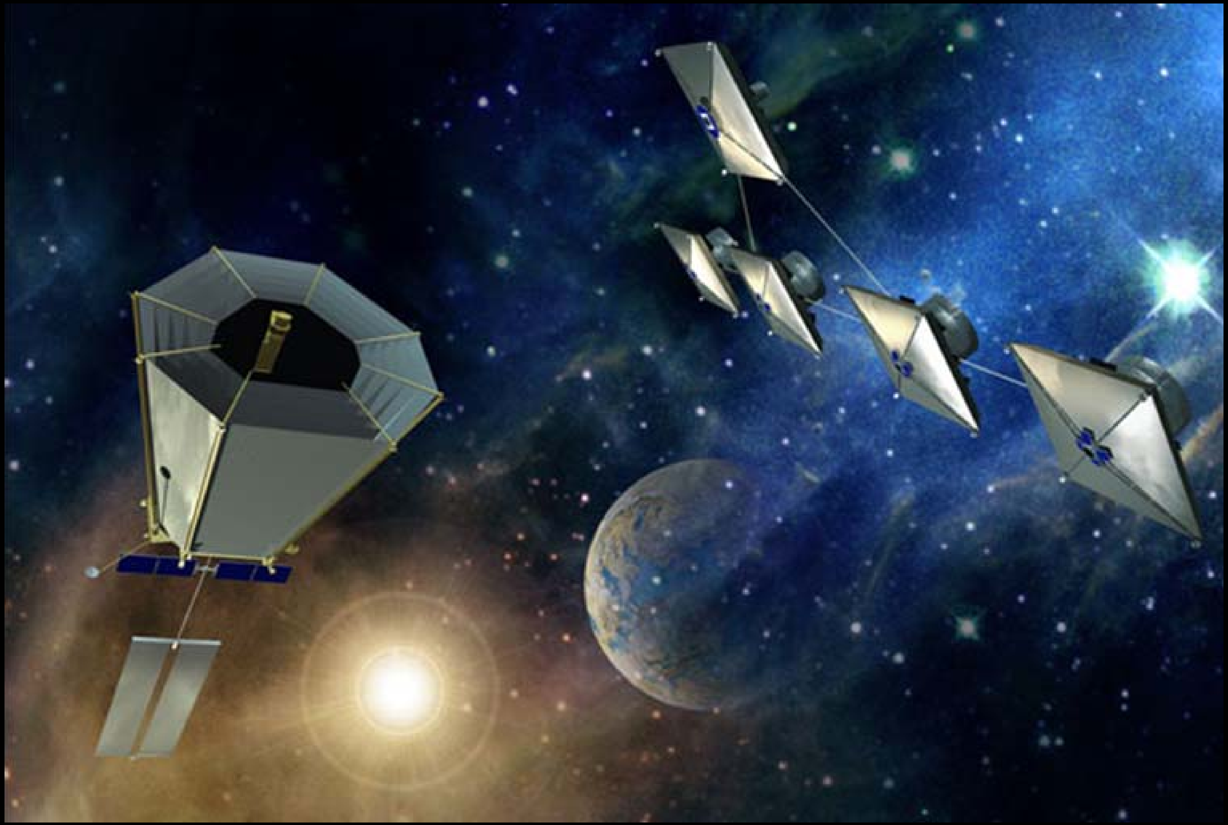
- **Hot Jupiter: edge-on rotation due to the tidal locking**
- **Saturn: 30 deg. inclined, but spin of the Sun is small**
- **Worse in either case, but still detectable potentially (S/N=1)**

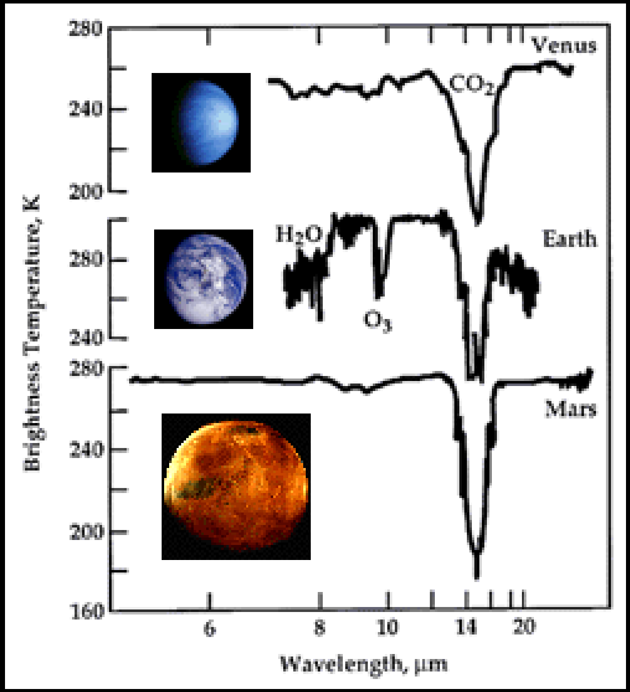
Future of transiting planet research: follow Hantaro Nagaoka

- Nagaoka's Saturn model of atom
  - Nagaoka: Phil. Mag. 7(1904) 445
  - ⇒ quantum atomic physics
- Transiting planets
  - Orbital angular momentum(**L**): radial velocity
  - Spin of star(**S**): Rossiter effect
  - Spin of planet(**s**): ring, satellite
- From planets to atomic physics
- From atomic physics to planets

写真 2：長岡半太郎（1865－1950）

V toward astrobiology





A possible roadmap of sciences of extrasolar planets

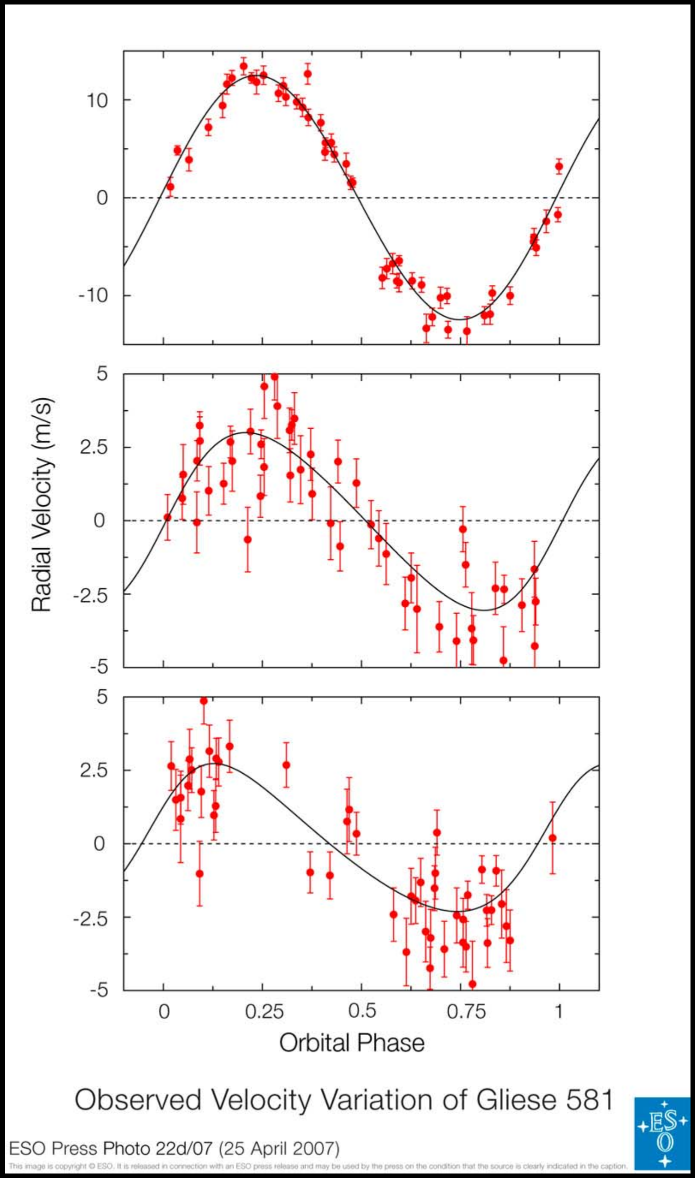
- Discovery phase of gas giant planets (1995-)
- Discovery of planetary atmosphere (2002)
- Detailed spectroscopic study of planets
- Discovery of IR emission of planets (2005)

- Discovery of visible reflection light
- Discovery of planetary ring
- Discovery of extrasolar planetary satellite
- Discovery of terrestrial planets

- ***Discovery of habitable terrestrial planet***
- ***Identifying biomarker***
  - Red-edge of extrasolar plant ?
- ***Discovery of extraterrestrial life***

Habitable terrestrial planet ?

- **"Super-Earth" ESO press release April 25, 2007**
  - **M-dwarf Gliese 581, 6.26pc**
- **Three planets**
  - **GL581b 15.6 M_E, P=5.4day**
  - **GL581c 5M_E, P=13.0day, 0～40℃？Rocky planet？**
  - **GL581d 7.7M_E, P=83.6d**



The Mainichi May 23, 2007

太陽系外の惑星発見

夢広がる「第二の地球」

欧州の天文学者チームが、太陽系から約20光年離れた宇宙で、地球によく似た惑星を発見した。生命が存在する可能性があるという。太陽以外の恒星を回る系外惑星は宇宙にどれほど存在するのか。生命のすむ「第二の地球」はあるのだろうか。【須田桃子】

◇生命居住可能域

今回見つかった惑星は、地球からてんびん座方向に約20光年離れた「グリーゼ581」という恒星を回っている。直径は地球の1・5倍、質量は最小で地球の5倍程度と推測され、岩石質の可能性がある。

惑星には、鉄の核と岩石のマントルでできた岩石質の地球型惑星と、木星のように水素やヘリウムの分厚いガスが主成分の巨大ガス惑星、さらに天王星のように氷と石の大きな核を薄いガスの層が覆う巨大氷惑星に分類される。このうち、生命をはぐくむ海を持つのに十分な量の大気が存在しうるのは、地球と同程度の質量の岩石質の惑星だけと考えられている。

グリーゼ581は太陽より小さい「赤色わい星」。惑星との距離は0・07天文単位（1天文単位は太陽－地球間の距離）。つまり地球と太陽の距離の約14分の1。惑星の平均表面温度はセ氏氷点下3～40度くらいとされる。大量の水があれば、海（液体）として存在するかもしれない。

須藤靖・東京大教授（宇宙物理学）は「ある惑星に生命が存在するかを調べるには、まず岩石質かどうかを確認し、次に大気を観測して水や酸素、オゾンがあるかを知る必要がある。今回の惑星はそうした観測の一つのターゲットで、第二の地球を探す上で重要な一里塚だ」と評価する。恒星から適当な距離にあり、液体の水が存在しうる「生命居住可能領域」で、岩石質らしき惑星が見つかったのは初めてだ。

◇惑星の見つけ方

惑星は自力では光らない。金星や木星が輝いているのは、太陽の光を反射しているからだ。しかし、地球から遠く離れた惑星では、その光をとらえるのは難しい。そこで、恒星を精密に観測し、間接的に惑星の存在を知る方法が編み出された。

惑星を持つ恒星は、公転する惑星の重力の影響を受け、わずかにふらつく。これにより、惑星と恒星の距離、惑星の質量が推測できる。惑星が恒星の前を横切るとき、惑星の影により恒星の見かけの明るさが1%程度弱まる。これから、惑星の大きさが計算できる。

赤色わい星「グリーゼ581」(中心)。赤色わい星は宇宙で最もありふれた恒星で、直径は太陽の3分の1以下、表面温度も3200度程度と低い＝欧州南天天文台提供

銀河系 160億恒星に可能性

系外惑星の探査は1940年代に始まった。最初の半世紀は目立った成果がなく、カナダの科学者が95年、長年の観測の末に「太陽以外の恒星の周りに惑星はない」とする論文を出すほどだった。しかし、その2カ月後、スイスの観測チームが初めて惑星を発見した。

ペガサス座51番星を回るこの惑星の質量は、木星の約半分。恒星との距離は0・05天文単位で、4・2日間で回っていた。木星と太陽の距離は5・2天文単位、12年間で回ることと比較すると、それまでの惑星の常識を覆す姿だった。

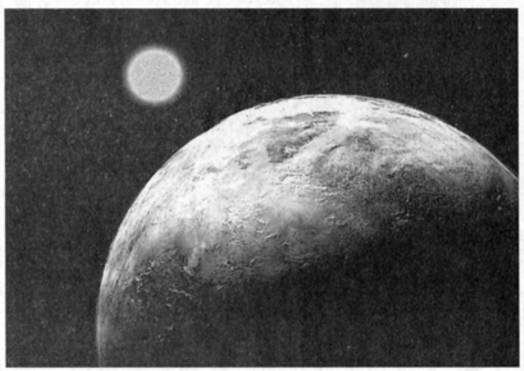
その後、世界の観測チームが、公転周期が数日という可能性も視野に入れ、新たに探査を開始。新惑星が続々と発見された。21日現在、確認された系外惑星は236個に上る。

◇探査衛星も出発

しかし、これまでに見つかった惑星の多くは、最初の惑星と同様、太陽系の惑星の姿とはほど遠い。恒星のすぐ近くを回るため、セ氏1000度を超える灼熱（しゃくねつ）の世界と予想される巨大ガス惑星。大きくゆがんだ楕円（だえん）軌道を回るため、灼熱と酷寒の世界を行き来する巨大惑星などだ。ただ、観測技術の向上やデータの蓄積により、最近では木星に似た長い公転軌道の惑星の発見も増えてきているという。井田茂・東京工業大教授（惑星物理学）は「これらの発見で、太陽系はそれほど珍しくないということが分かってきた」と説明する。

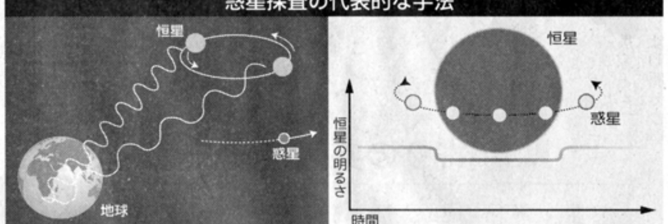
では、人類は地球外生命に出会えるのか。井田教授は生命居住可能領域に地球型惑星を持つ恒星の割合を「全恒星の10%程度」と見積もる。銀河系内ではおよそ160億個が該当する。

地球型惑星を探そうと、仏は昨年12月、探査衛星「CoRoT」を打ち上げた。米も08年中に同じ目的の衛星を打ち上げる予定だ。「人類は世界を知りたい、自分たちを知りたい、という思いをエネルギーに進化を遂げてきた。系外惑星探査は、その根源的な好奇心につながる研究なのです」と井田教授は語る。



今回発見された地球とよく似た惑星の想像図（手前）。左奥は「グリーゼ581」＝欧州南天天文台提供

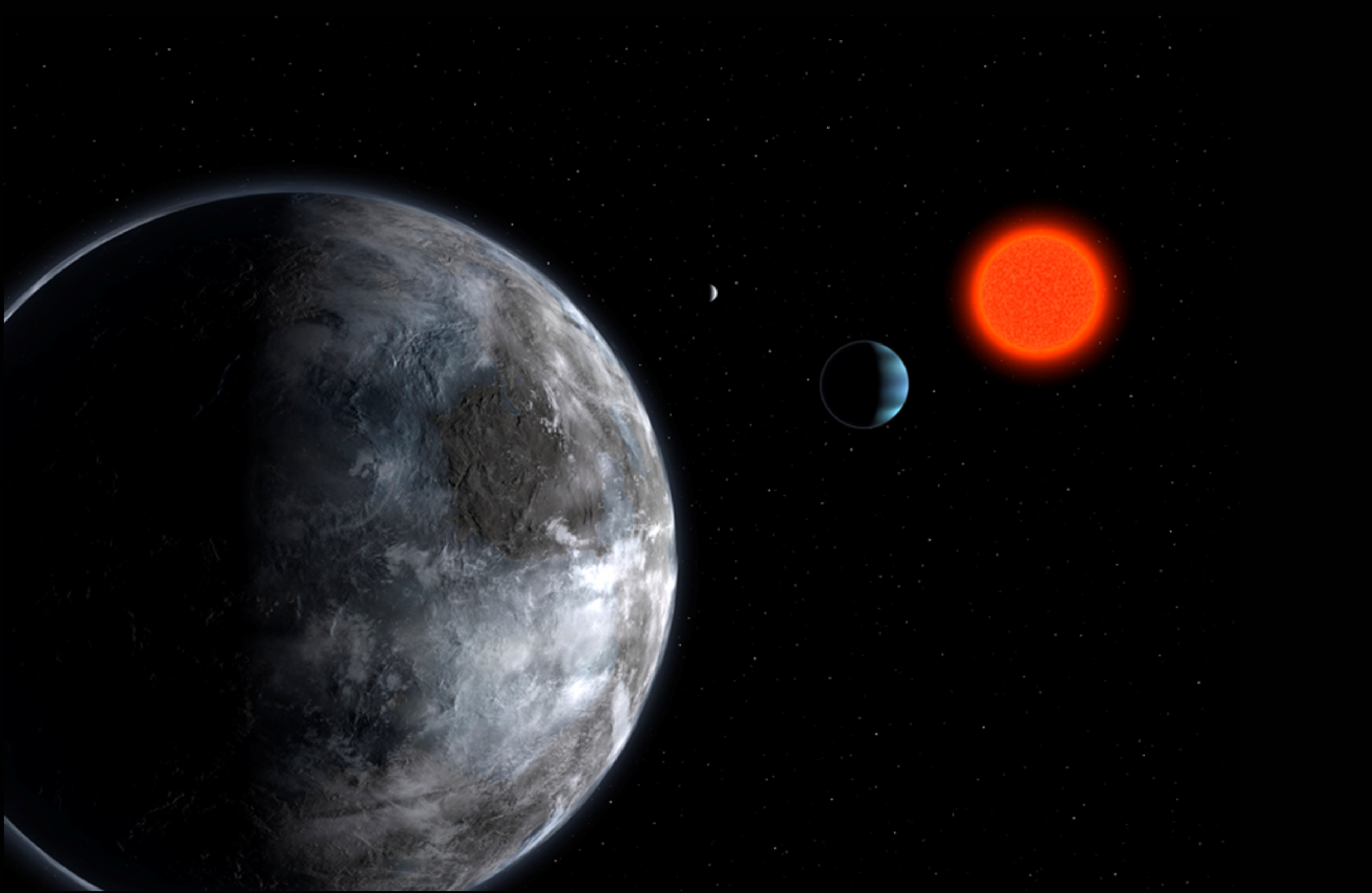
惑星探査の代表的な手法



欧州南天天文台のホームページなどから作成

㊧惑星の重力の影響で、恒星はわずかにふらつく。救急車の音が近づく時高く、遠ざかる時低くなるのと同じドップラー効果で、地球に届く恒星の光は周期的に変化する。
㊨惑星が恒星の前を横切ると、惑星の影で恒星の見かけの明るさが一時的に弱まる。この度合いは恒星と惑星の断面積の比に対応する。㊧の方法である程度の質量、㊨の方法で大きさが分かり、組み合わせて惑星の密度を求める。

A Super-Earth around Gliese 581



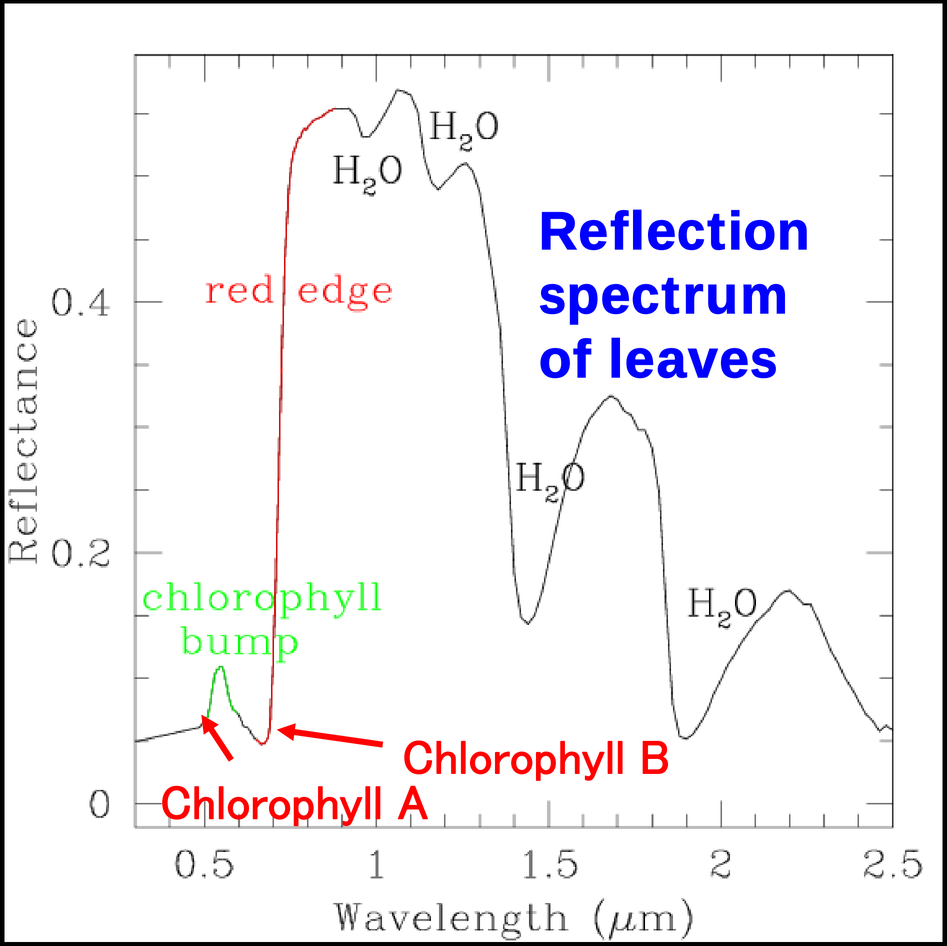
Astrobiology ?   Not yet

- 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

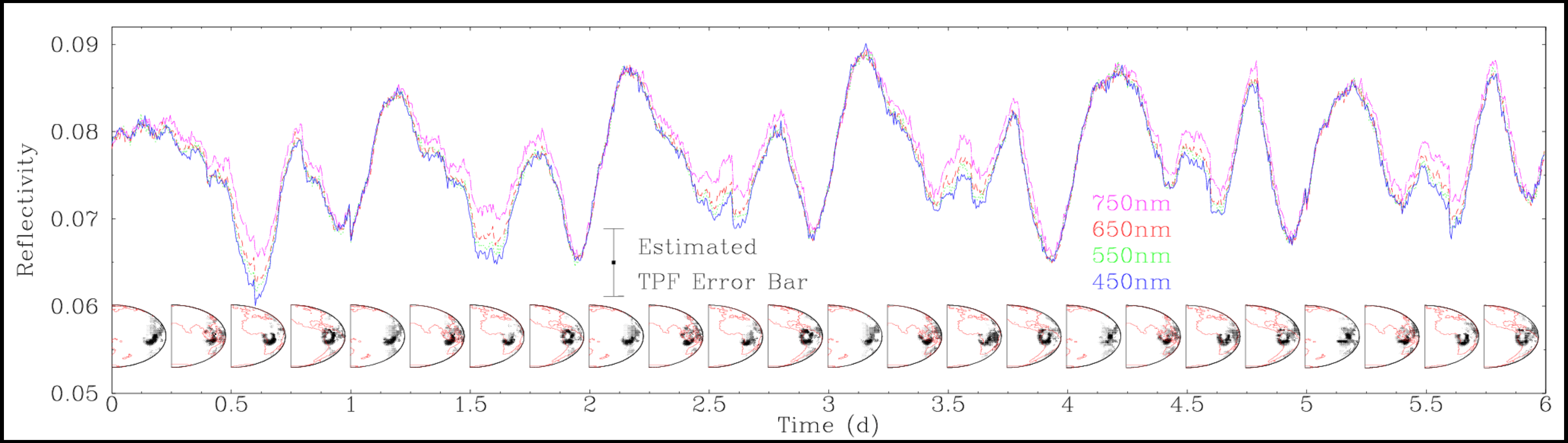
Red edge of (extrasolar) plants: a biomarker in extrasolar planets

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



Seager, Ford & Turner astro-ph/0210277

Expected daily change of the reflected light from the earth

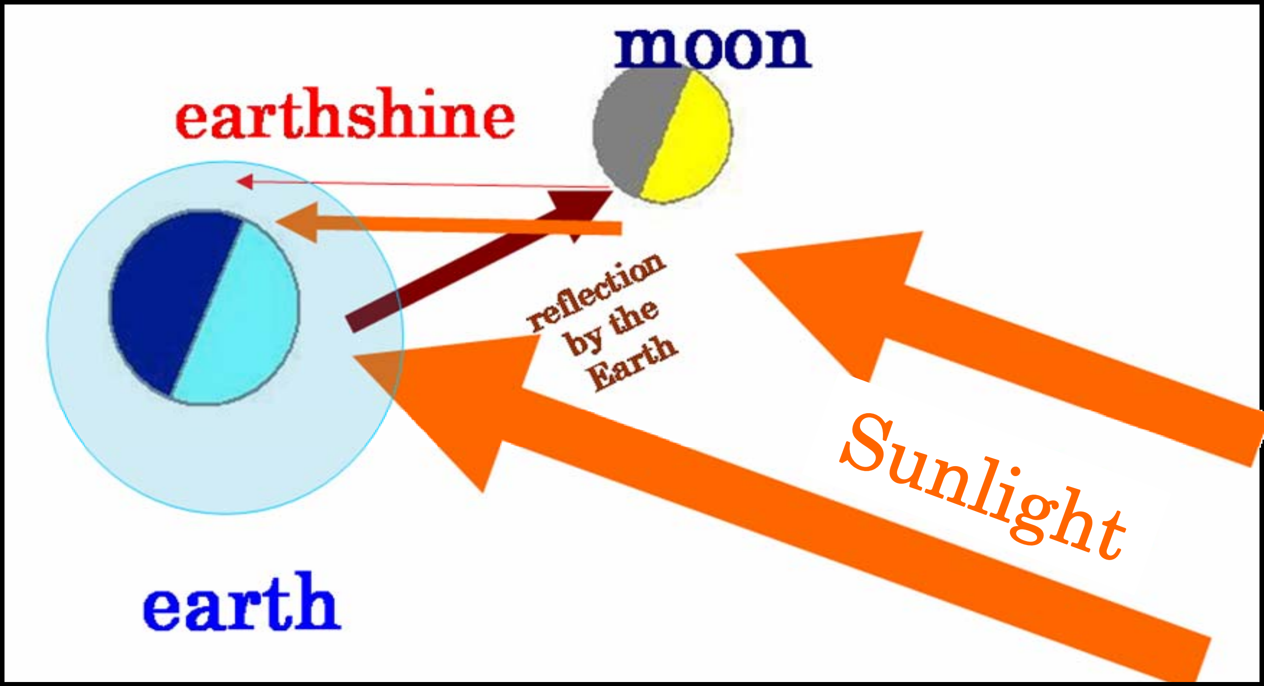


Ford, Seager & Turner: Nature 412 (2001) 885

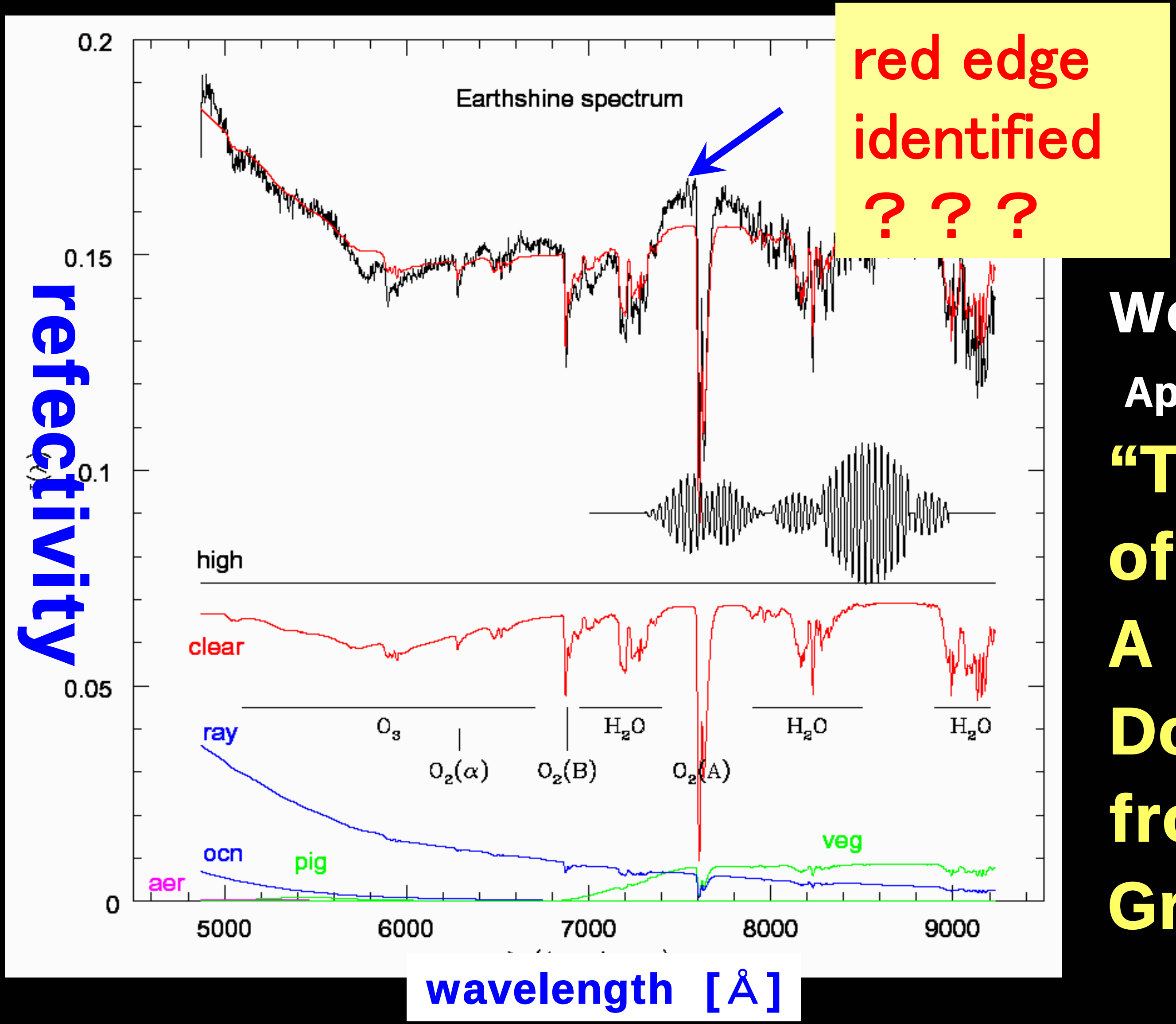
- ***Assume*** **that the earth's reflected light is completely separated from the Sun's flux !**
  - **TPF (Terrestrial Planet Finder) in (10～20) years from now ?**
- ***Periodic change of 10% level*** **due to different reflectivity of land, ocean, forest, and so on**
- **Cloud is the most uncertain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

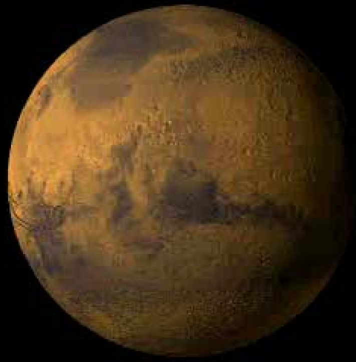
Vesto Melvin Slipher (1875-1969)

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

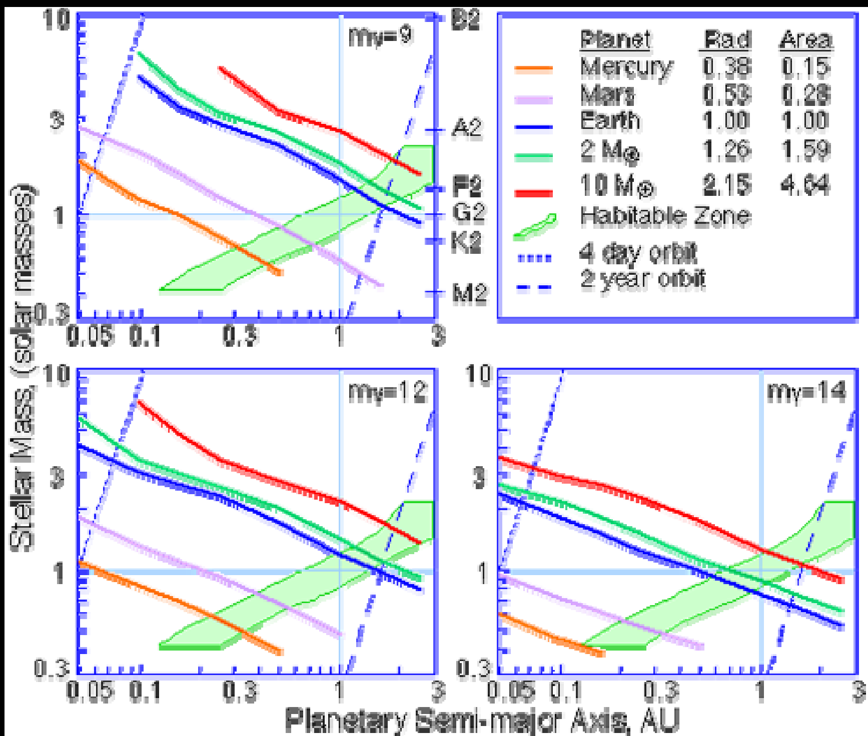


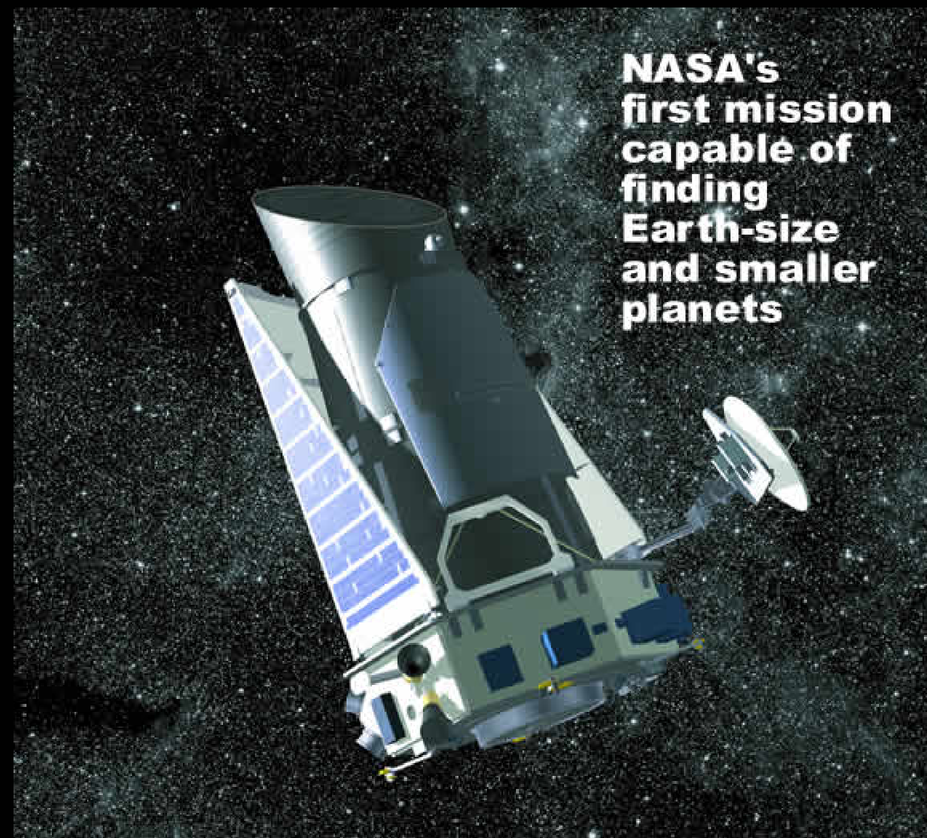
reflection spectrum. The Martian spectra of the dark regions so far do not give any certain evidence of the typical reflection spectrum of chlorophyl. The amount and types of vegetation required to make the effect noticeable is being investigated by suitable terrestrial exposures.

Astrobiology indeed in 1924 !

Kepler mission (June 2008 launch?)

differential photometry survey of transit planets
expect to discover > 50 terrestrial planets in 4 years ?





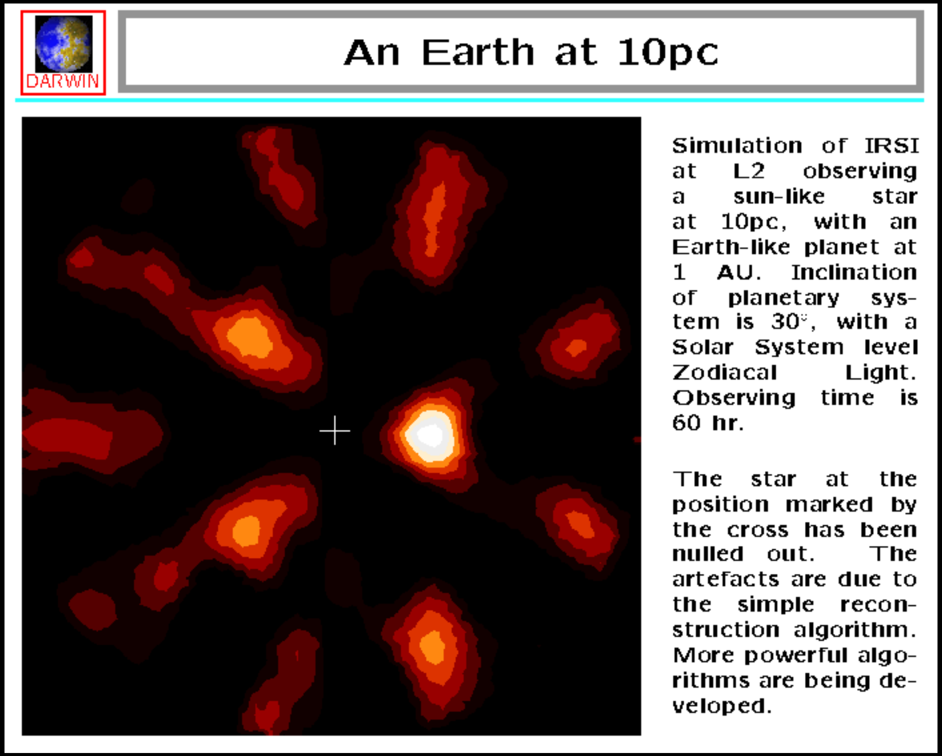
Kepler
A Search For Habitable Planets

http://kepler.nasa.gov/

Kepler mission (2008)

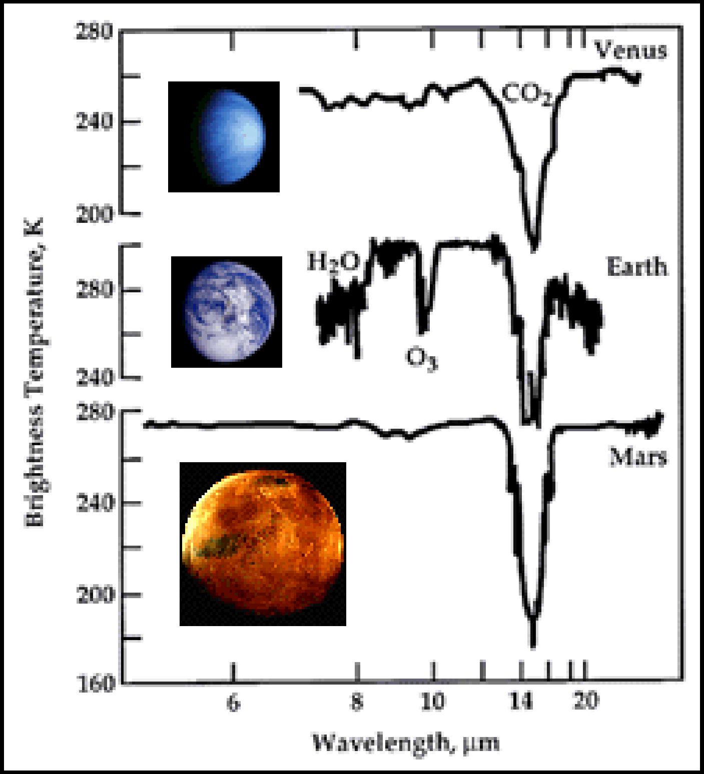
Darwin (ESA: launch after 2015)

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 extra-terrestrial life simply from remote observations ? Biomarker !!!

Future prospects

- **exciting era of extrasolar planet research**
  - **Just like cosmology in 1965 (Penzias and Wilson) or in 1992 (COBE)**
  - **Simply 10-40 years behind ? i.e., bright future !**
- **What if we discover more than 1000 terrestrial planets in the next decade ?**
  - **Just like cosmology in 2006 (WMAP+others) ?**
- ***How to convince ourselves of the presence of extra-terrestrial life simply from remote observations ?***
  - **Precision extrasolar planet research ?**
  - **Go (back) to SETI after all ?**
  - **Ultra-precise spectroscopy is the key !**