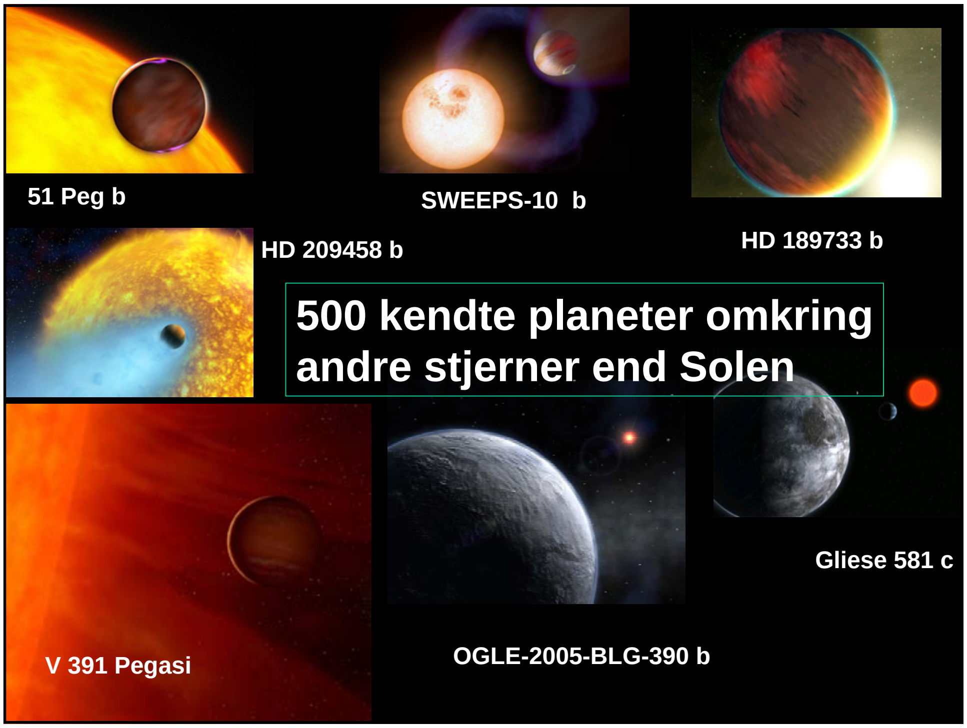
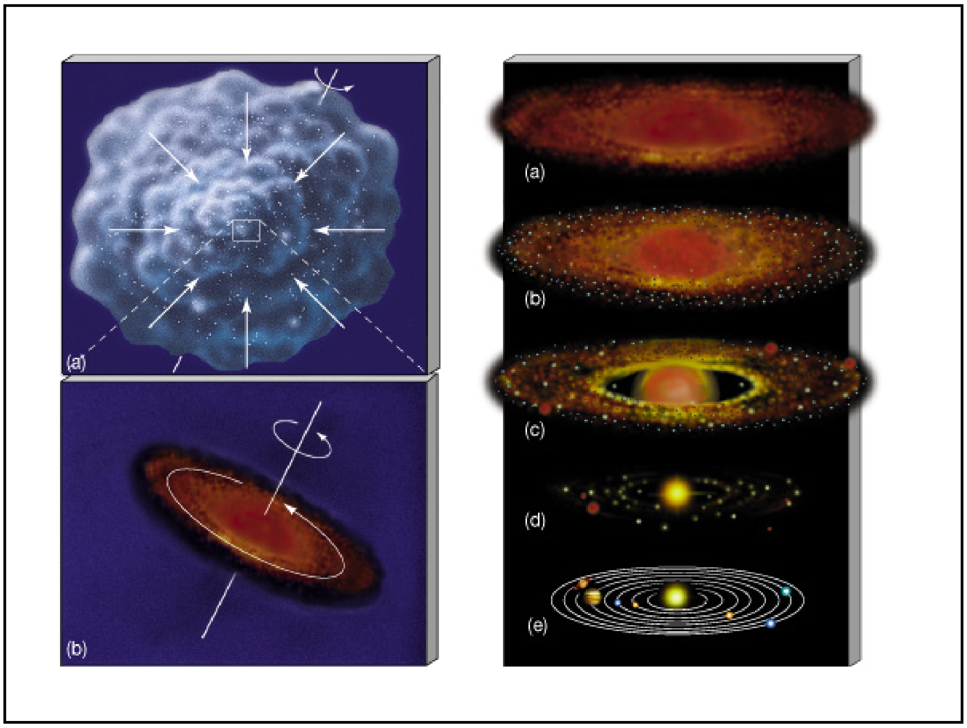

Planeter omkring andre stjerner end Solen
Hans Kjeldsen
Institut for Fysik og Astronomi


Exoplaneter…

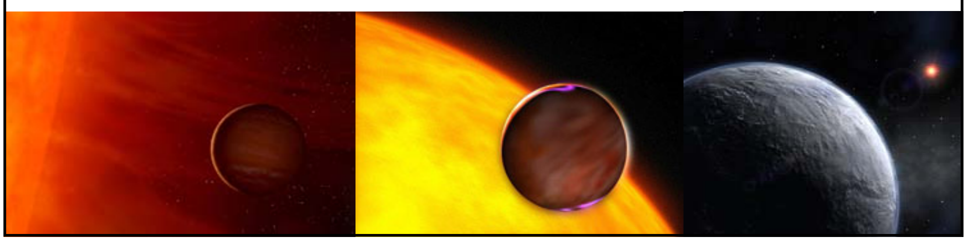

51 Peg b
SWEEPS-10 b
HD 189733 b
HD 209458 b
500 kendte planeter omkring andre stjerner end Solen
Gliese 581 c
V 391 Pegasi
OGLE-2005-BLG-390 b


51 Peg b
HD 189733 b
Findes der andre planeter som Jorden?
Gliese 581 c
V 391 Pegasi
OGLE-2005-BLG-390 b


(a)
(b)
(a)
(b)
(c)
(d)
(e)

Hvordan finder man en exoplanet?

- Direkte observation
- Via tyngdekraften: radialhastigheden og positionen af moderstjernen
- Via rummets krumning – tyngdefeltet
- Via passage foran moderstjernen



Hvordan finder man en exoplanet?

- Direkte observation
- **Via tyngdekraften: radialhastigheden og positionen af moderstjernen**
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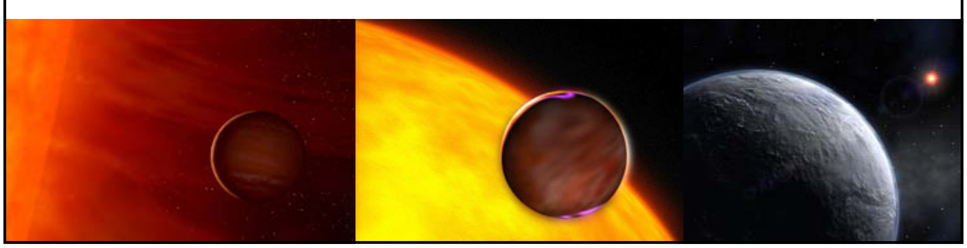
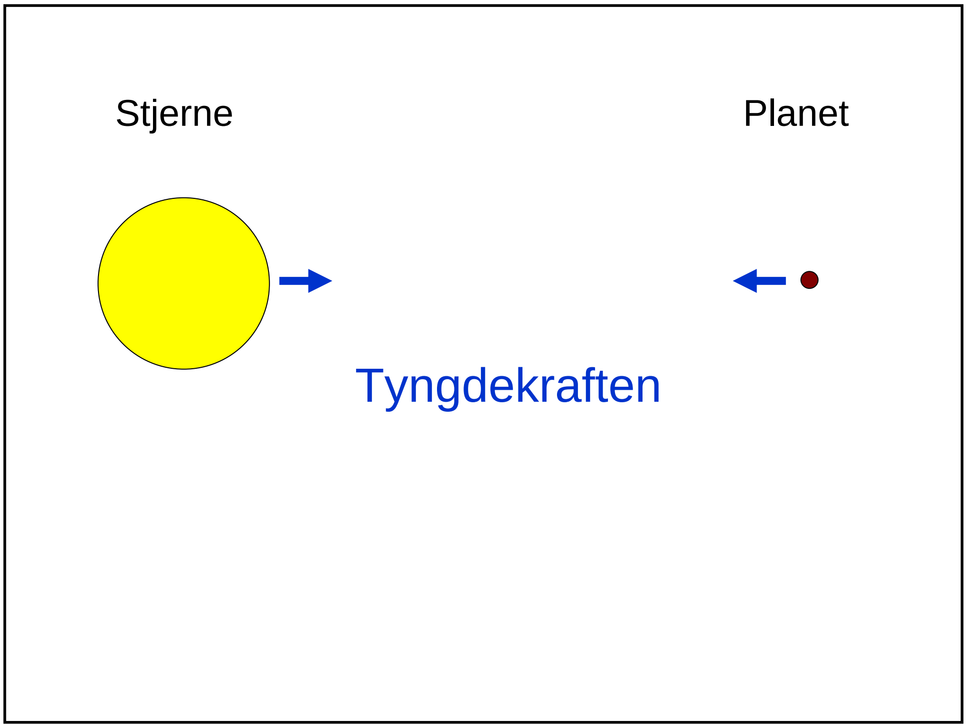
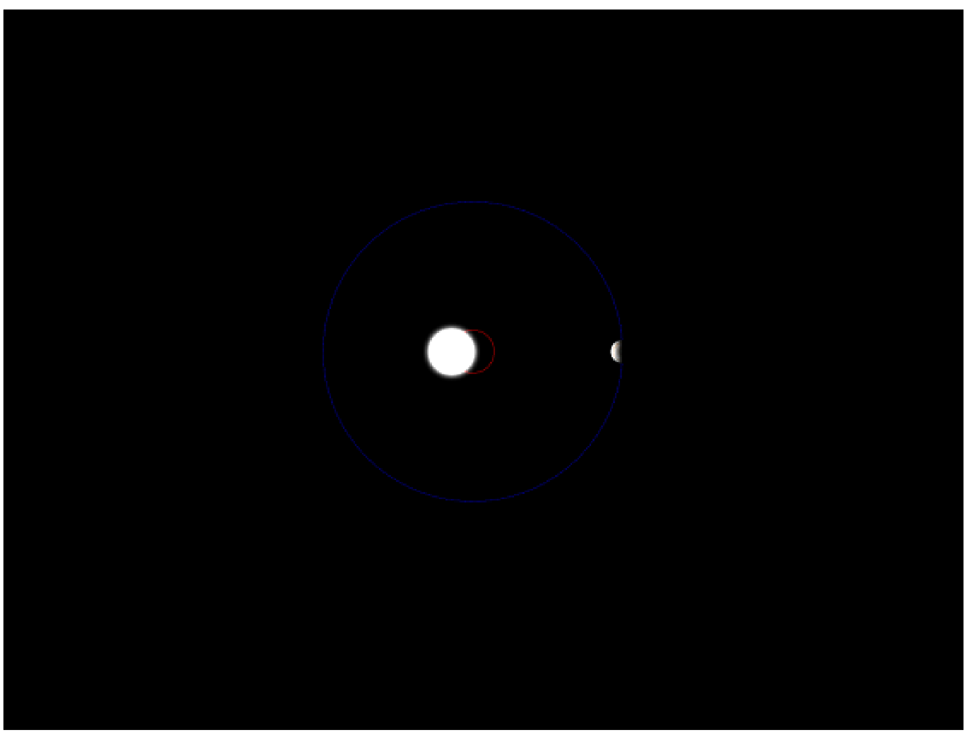



Stjerne
Planet
Tyngdekraften



instrumental variations during exposure.

The first observations of 51 Peg started in September 1994. In January 1995 a first 4.23-days orbit was computed and confirmed by i

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Michel Mayor & Didier Queloz
NATURE – VOL 378 – 23 November 1995

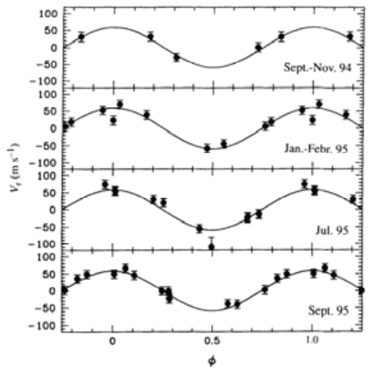

FIG. 2 Orbital motion of 51 Peg at four different epochs corrected from the γ-velocity. The solid line represents the orbital motion fitted on each time span with only the γ-velocity as a free parameter and with the other fixed parameters taken from Table 1.

at a 200 m s^{-1} level. Intensive monitoring of 51 Peg is in

to confirm this long-period orbit.

In Fig. 4 a short-period circular orbit is fitted to the da

γ-velocity. Leaving the ecc

ve given $e = 0.09 \pm 0.06$ wit

for the r.m.s. residual (13

circular orbit cannot be ru

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neters of the circular-orbit s

An orbital period of 4.23 days is rather short, but shor binaries are not exceptional among solar-type stars. (Fi troscopic binaries have been found with a period <4 d volume-limited sample of 164 G-type dwarfs in th vicinity[6].) Although this orbital period is not surprising i stars, it is puzzling when we consider the mass obtained companion:

$$M_2 \sin i = 0.47 \pm 0.02\ M_J$$

where i is the (unknown) inclination angle of the orbit.

51 Peg (HR8729, HD217014 or Gliese 882) is a 5.5 m quite similar to the Sun (see Table 2), located 13.7 light yr) away. Photometric and spectroscopic analyses a star slightly older than the Sun, with a similar tem and slight overabundance of heavy elements. The estima derived from its luminosity and effective temperature is of an old galactic-disk star. The slight overabundance c elements in such an old disk star is noteworthy. But thi tainly not a remarkable peculiarity in view of the o scatter of stellar metallicities at a given age.

Upper limit for the companion mass

A priori, we could imagine that we are confronted with a spectroscopic binary with an orbital plane almost perpe to the line of sight. Assuming a random distribution o orbital planes, the probability is less than 1% that the con mass is larger than 4 M_J, and 1/40,000 that it is above th

Michel Mayor & Didier Queloz
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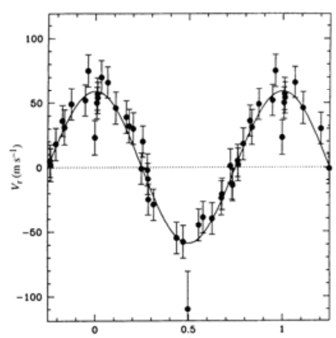


FIG. 4 Orbital motion of 51 Peg corrected from the long-term variation of the γ-velocity. The solid line represents the orbital motion computed from the parameters of Table 1.

ogen-burning limit of 0.08 $M_\odot$. Although these probability esti-

TABLE 2 Physical parameters of 51 Peg compared with those of the Sun

	Sun	51 Peg Geneva photometry*	Spectroscopy†	Strömgren photometry and spectroscopy[11]
T_{eff} (K)	5,780	5,773	5,724	5,775
log g	4.45	4.32	4.30	4.18
Fe/H	0		0.19	0.06‡
M/H	0	0.20		
M_v	4.79	4.60		
$R/R_\odot$	1	1.29		

M/H is the logarithmic ratio of the heavy element abundance compared to the Sun (in dex).

* M. Grenon (personal communication).

† J. Valenti (personal communication).

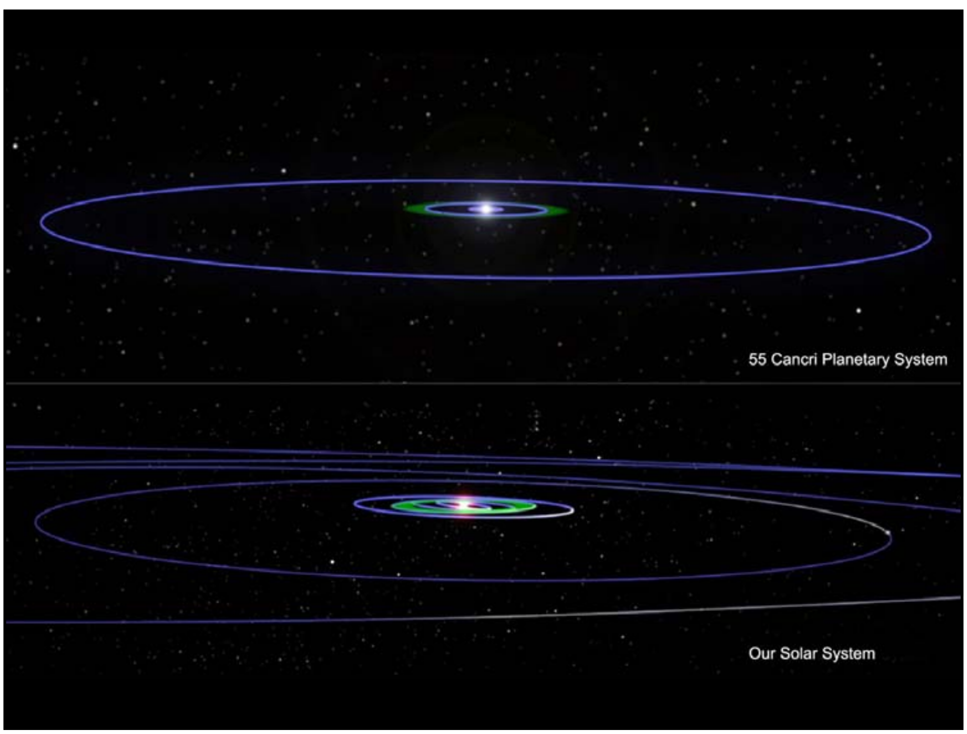
‡ But other elements such as Na I, Mg I, Al I are overabundant, in excess of 0.20.

puted if a 25% uncertainty in the period determination is assumed.

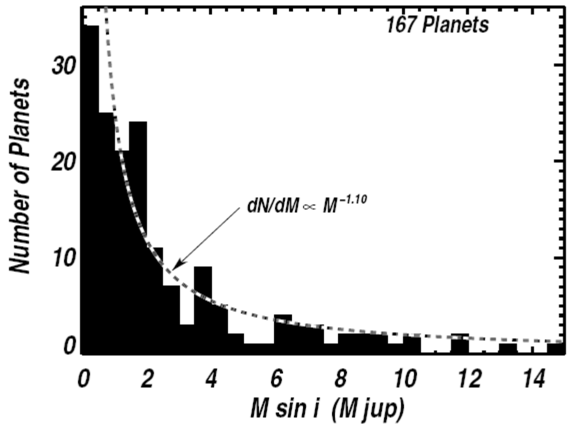
Using the mean $v \sin i$ and the rotational velocity computed from chromospheric activity, we finally deduce a lower limit of 0.4 for sin i. This corresponds to an upper limit for the mass of the planet of 1.2 M_J. Even if we consider a misalignment as large as 10°, the mass of the companion must still be less than 2 M_J.

#	Planet:	Per(d)	v (m/s)	e	Omega
2	55 Cnc b	14.6524(100)	73.38(82)	0.01(13)	168(33)
3	55 Cnc c	44.36(25)	9.60(86)	0.071(12)	115(11)
5	55 Cnc d	5552(78)	47.5(1.5)	0.091(80)	181.6(6.7)
1	55 Cnc e	2.7955(20)	5.80(81)	0.09(28)	187(41)
4	55 Cnc f	260.0(1.1)	4.88(60)	0.20(20)	181(60)

Planet:	M sin(i)/M(Jup)	a/AU
55 Cnc b	0.833	0.114
55 Cnc c	0.157	0.238
55 Cnc d	3.90	5.97
55 Cnc e	0.0377	0.0377
55 Cnc f	0.142	0.774



http://exoplanets.org/figures.html



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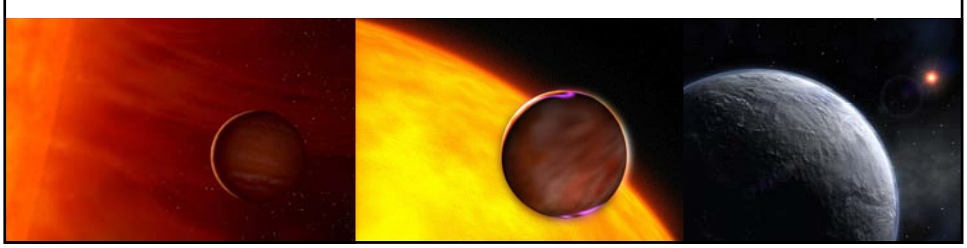

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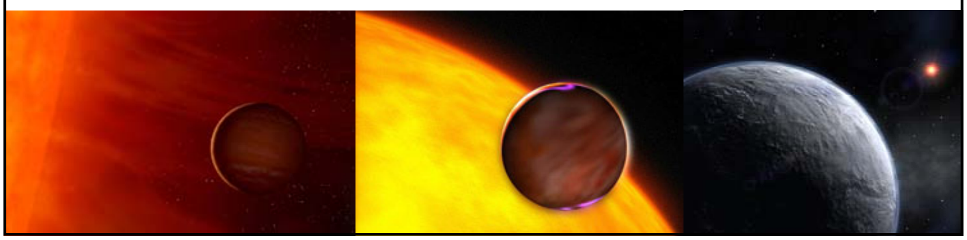

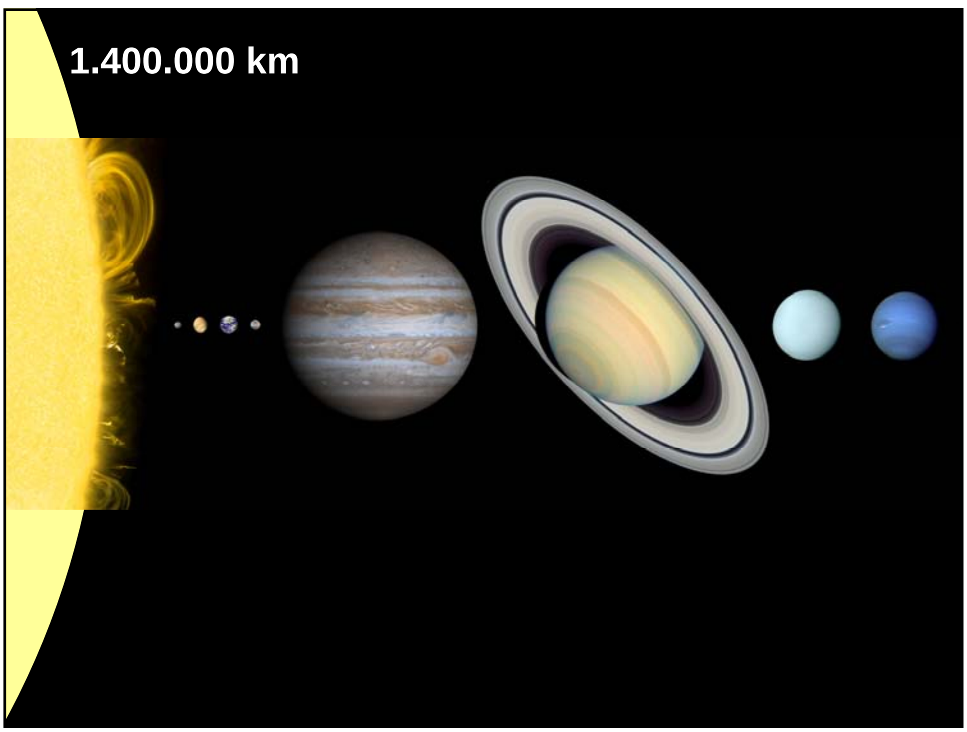

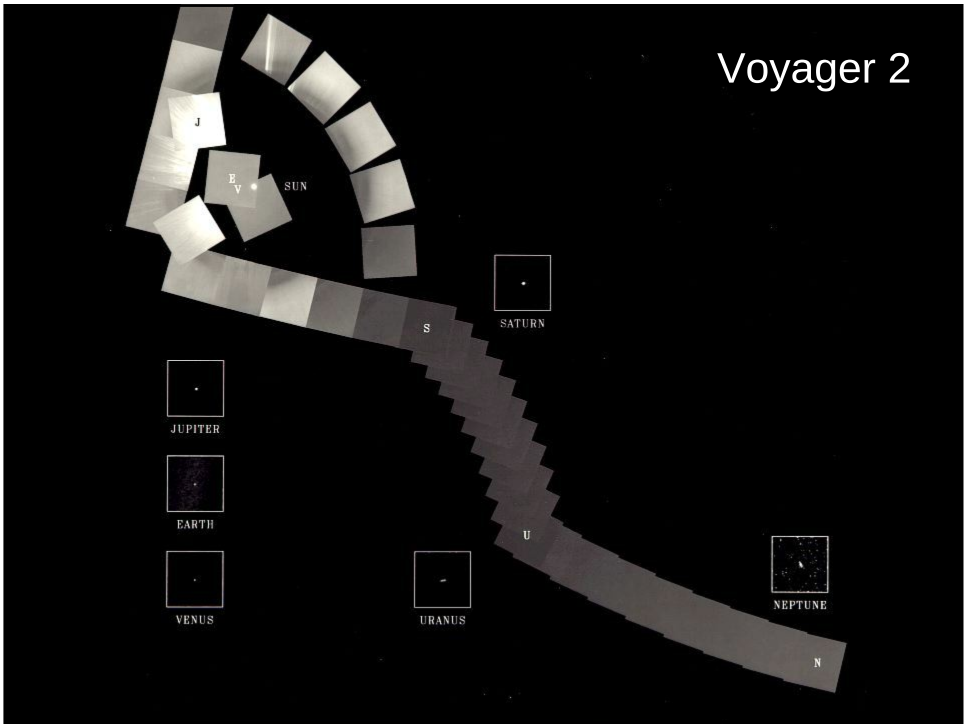
Voyager 2
J
E
V
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SATURN
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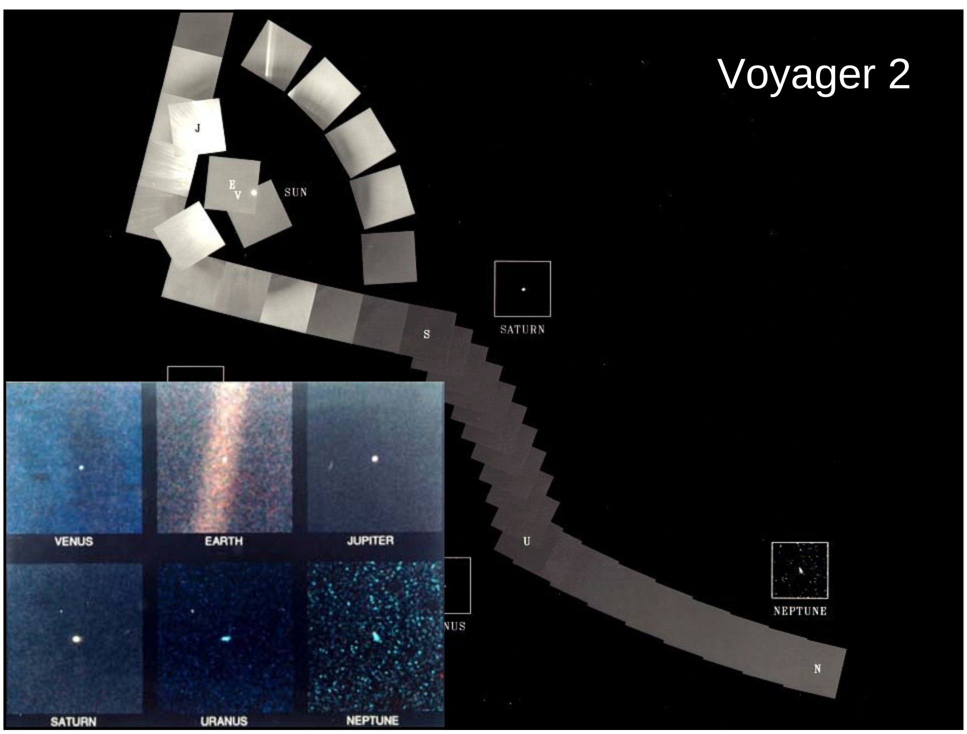
JUPITER
EARTH
VENUS
U
URANUS
NEPTUNE
N


Voyager 2
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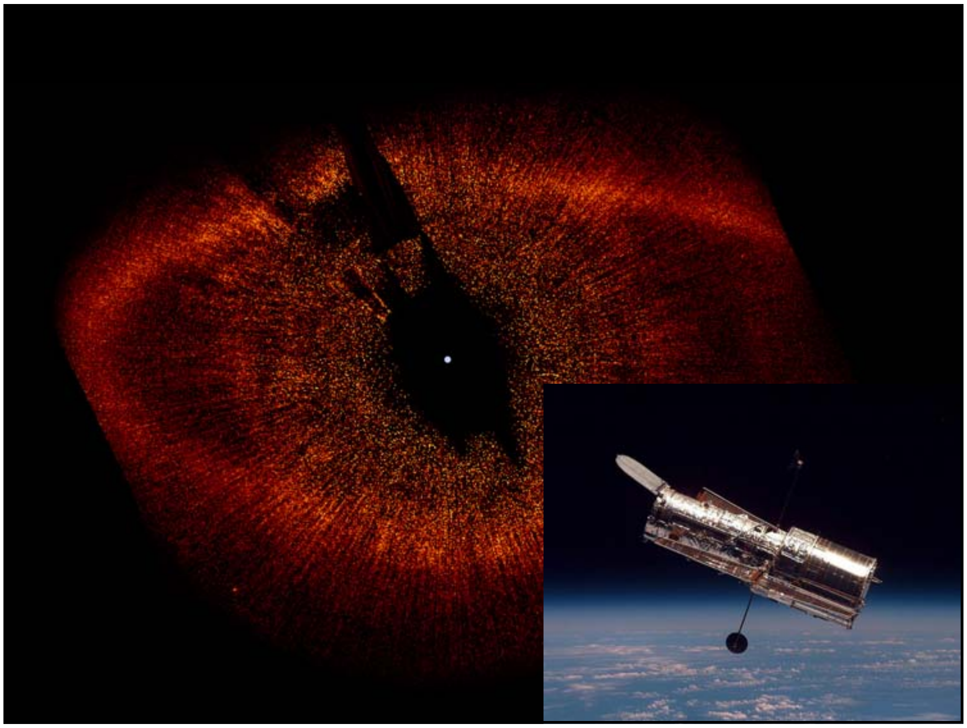
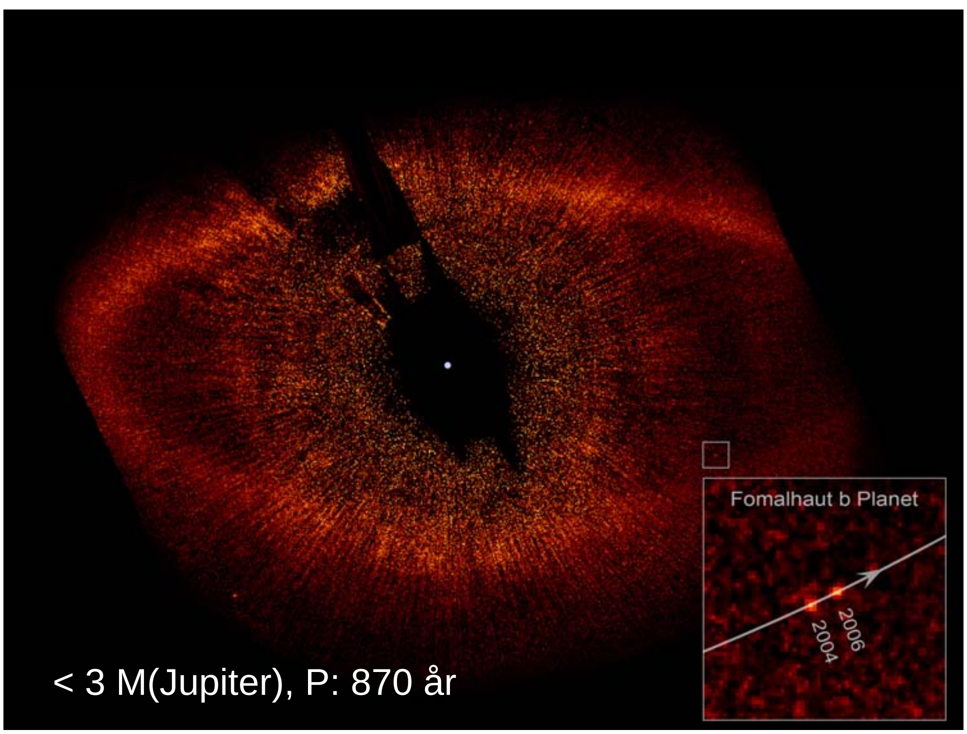
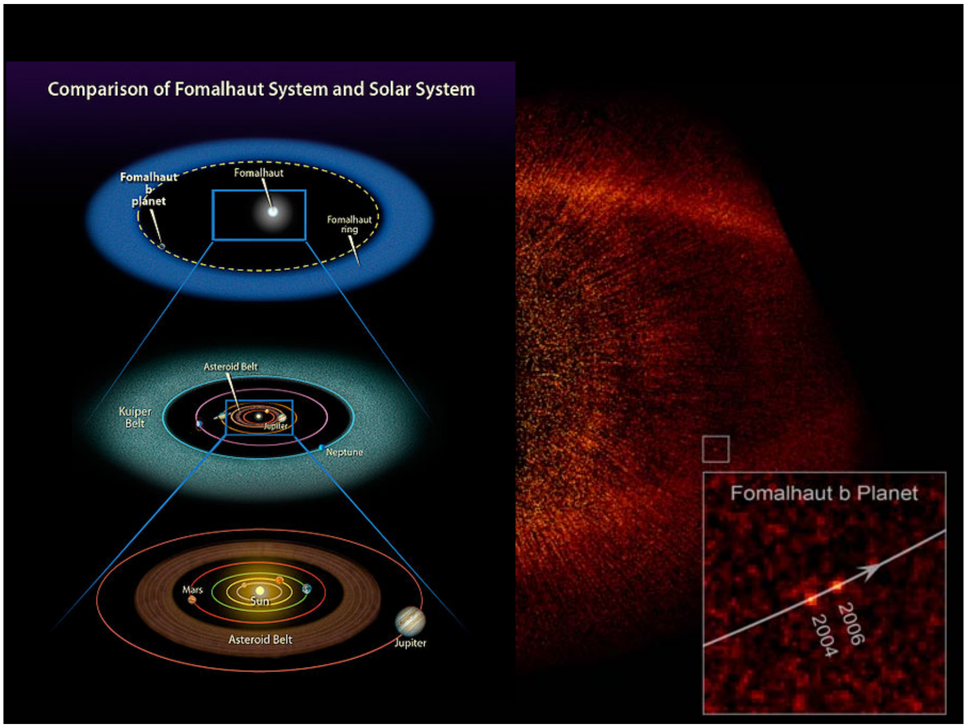
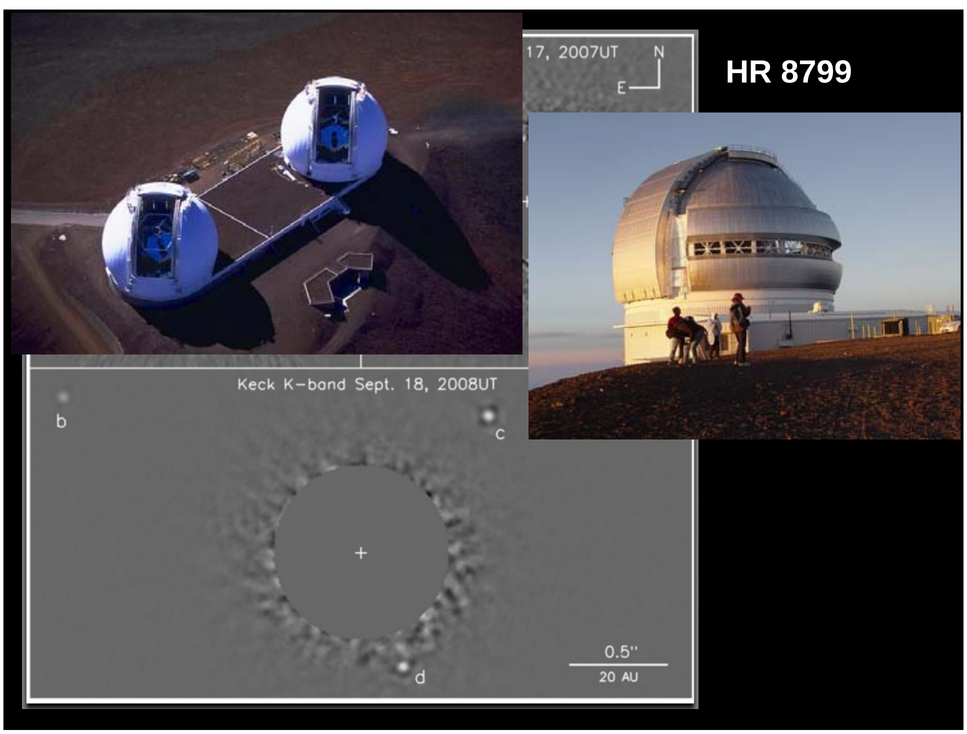
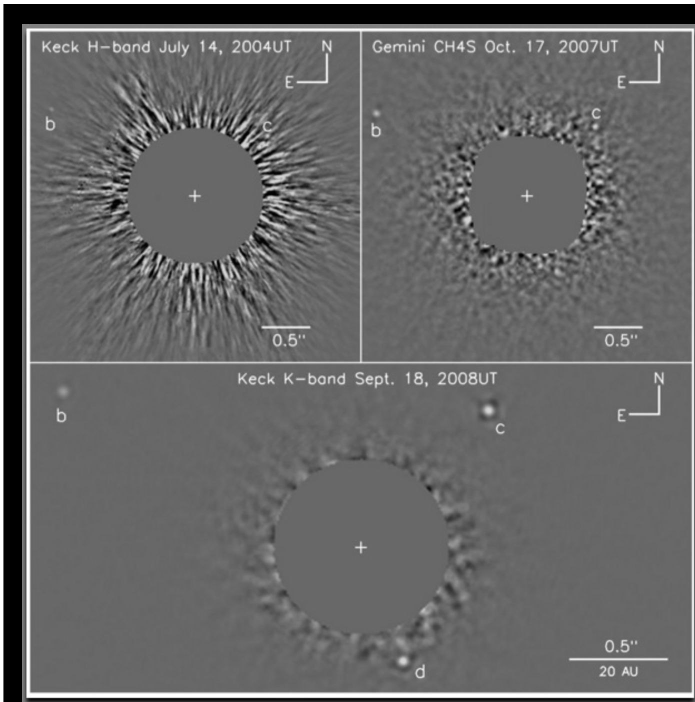



Fomalhaut b Planet
2006
2004
< 3 M(Jupiter), P: 870 år


Comparison of Fomalhaut System and Solar System
Fomalhaut b planet
Fomalhaut
Fomalhaut ring
Asteroid Belt
Kuiper Belt
Jupiter
Neptune
Mars
Sun
Asteroid Belt
Jupiter
Fomalhaut b Planet
2004
2006

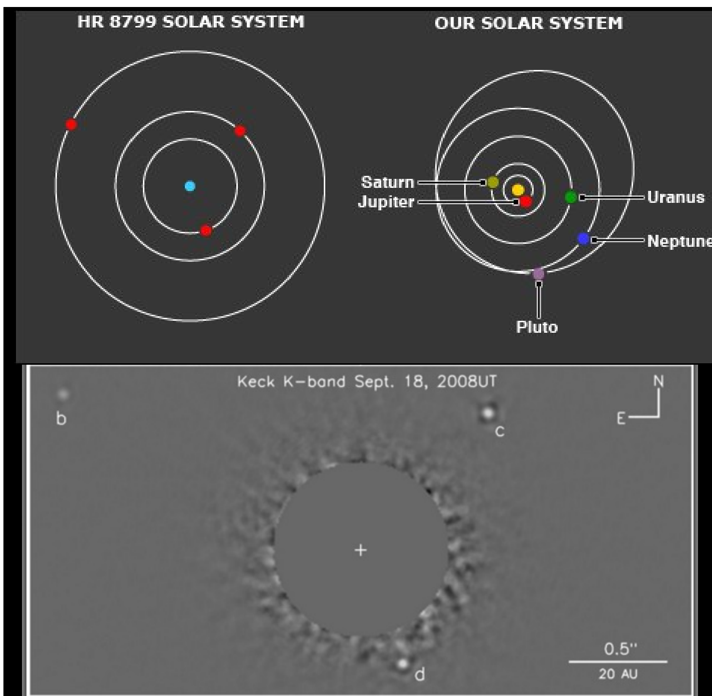

HR 8799
17, 2007UT
N
E
Keck K-band Sept. 18, 2008UT
b
c
d
0.5''
20 AU



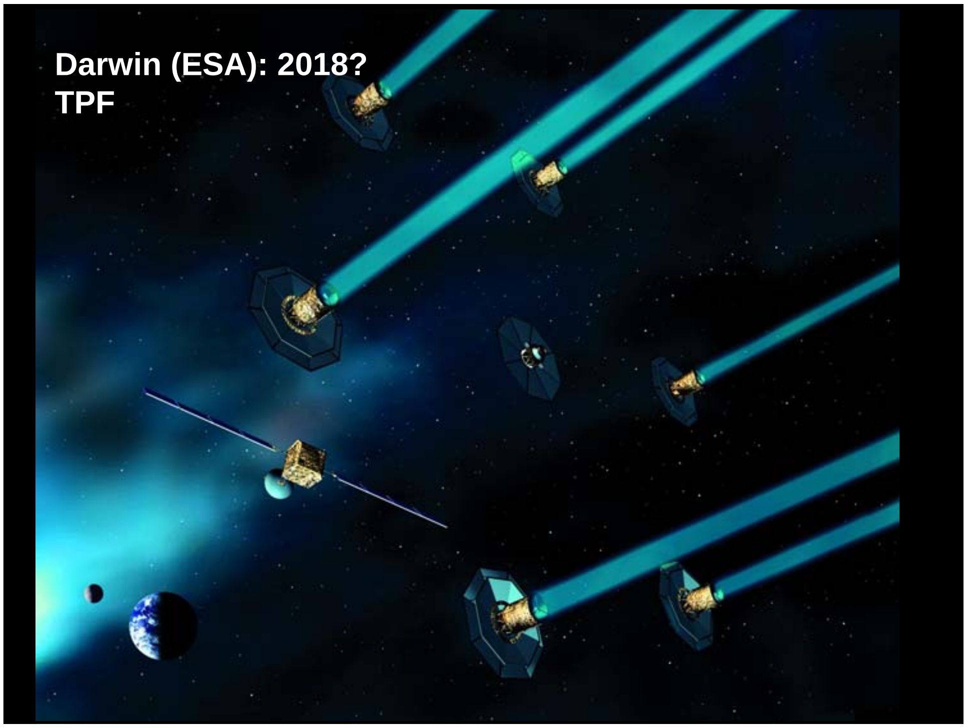
HR 8799

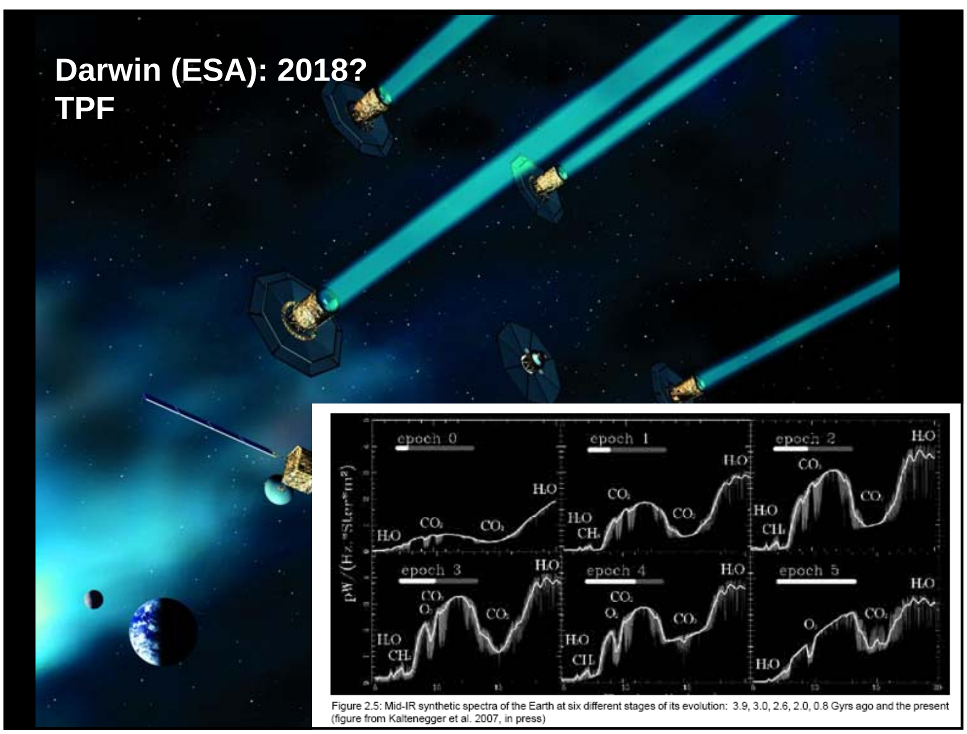
7-10 M(Jupiter)

P: 100, 190, 460 år

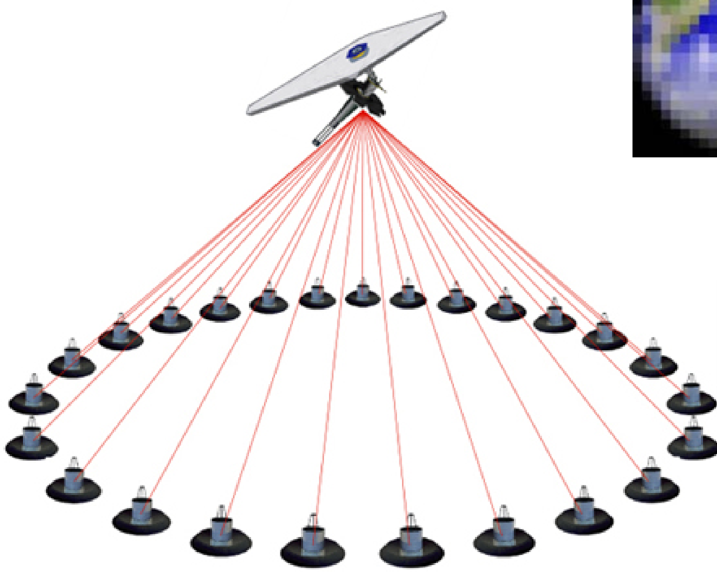


HR 8799


Darwin (ESA): 2018?
TPF


Darwin (ESA): 2018?
TPF
epoch 0
epoch 1
epoch 2
epoch 3
epoch 4
epoch 5
Figure 2.5: Mid-IR synthetic spectra of the Earth at six different stages of its evolution: 3.9, 3.0, 2.6, 2.0, 0.8 Gyrs ago and the present (figure from Kaltenegger et al. 2007, in press)

TPI (NASA): 2080?



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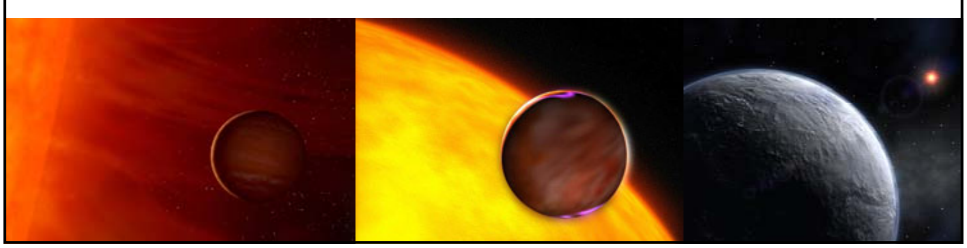

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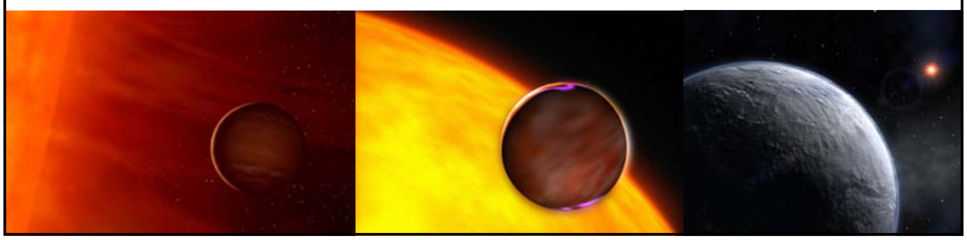
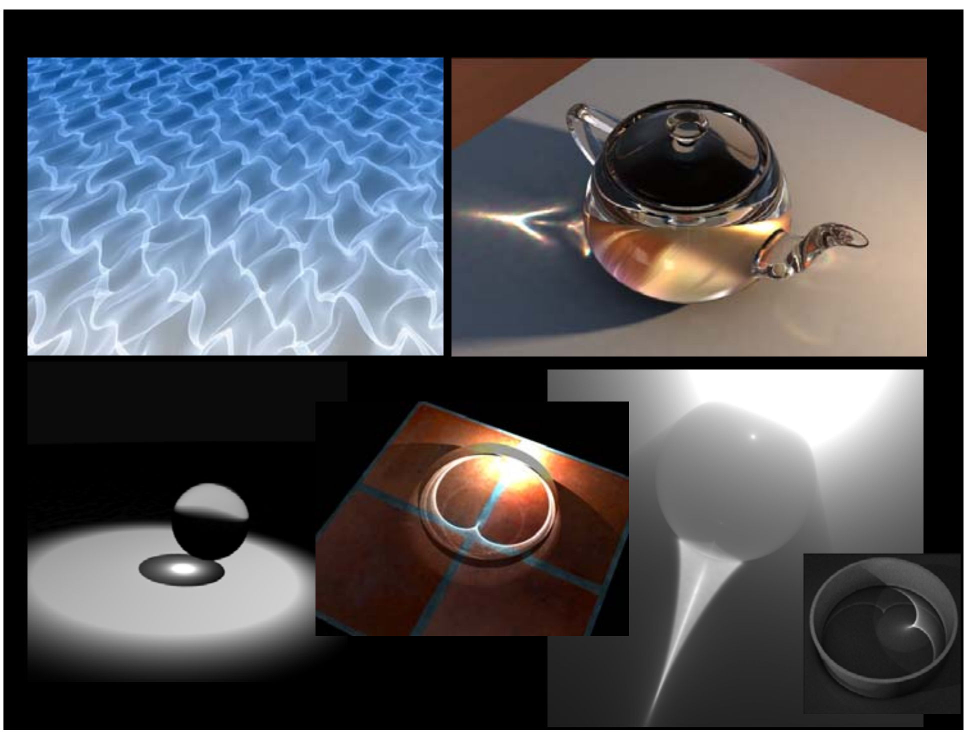




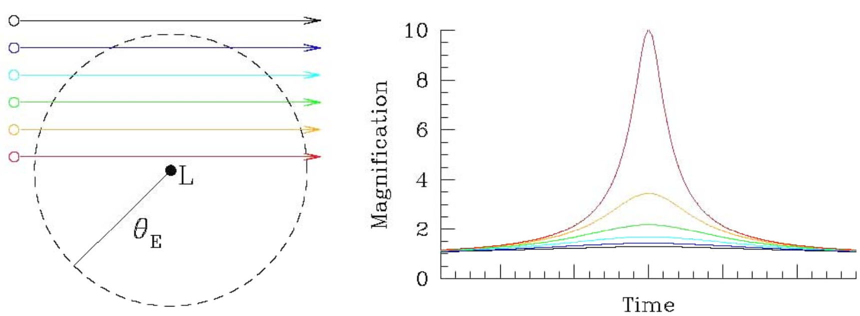


Fig. 12 — **Left:** Equally-probable source trajectories. **Right:** The corresponding single microlens light curves.

Caustic Curve

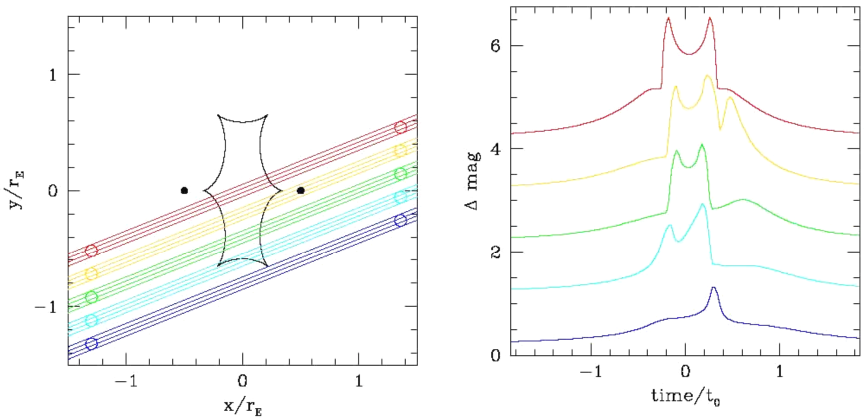
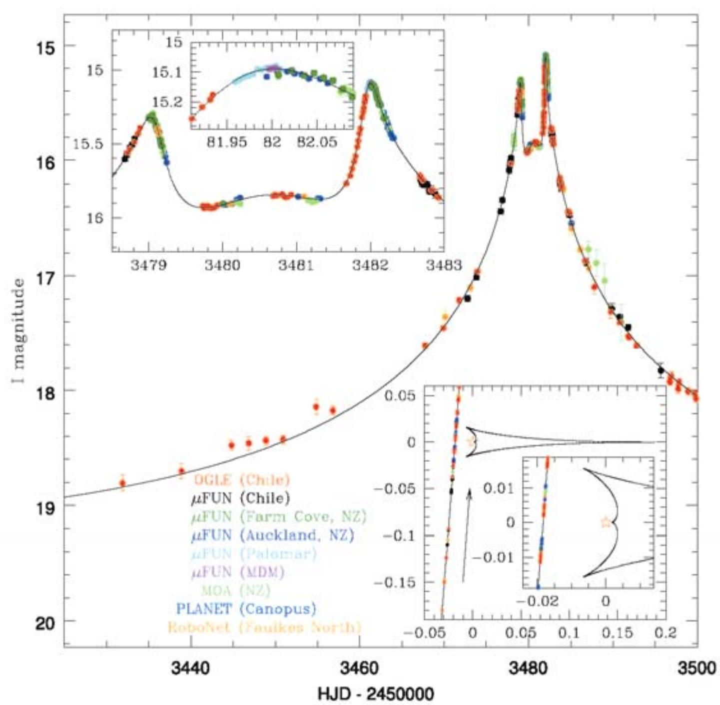
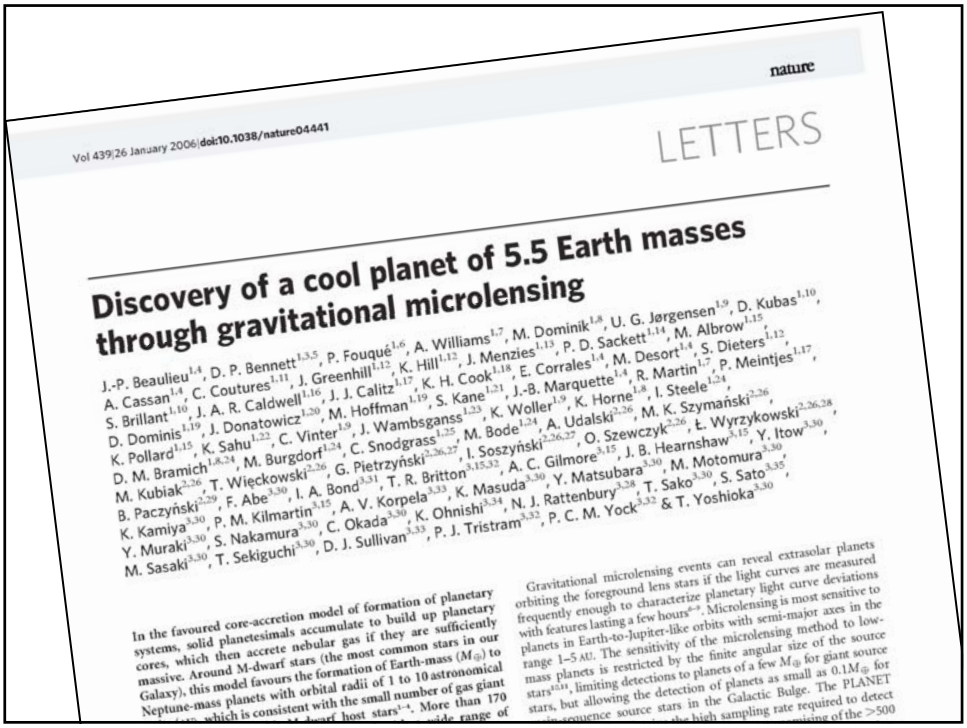


Fig. 13 — **Left:** The caustic (thick closed line) for two equal mass lenses (dots) is shown with several possible source trajectories. Angular distances are scaled to the Einstein ring radius of the combined lens mass. **Right:** The light curves resulting from the source trajectories shown at left; the temporal axis is normalized to the Einstein time t_E for the combined lens. (Adapted from Paczyński 1996.)





Vol 439|26 January 2006|doi:10.1038/nature04441

nature

LETTERS

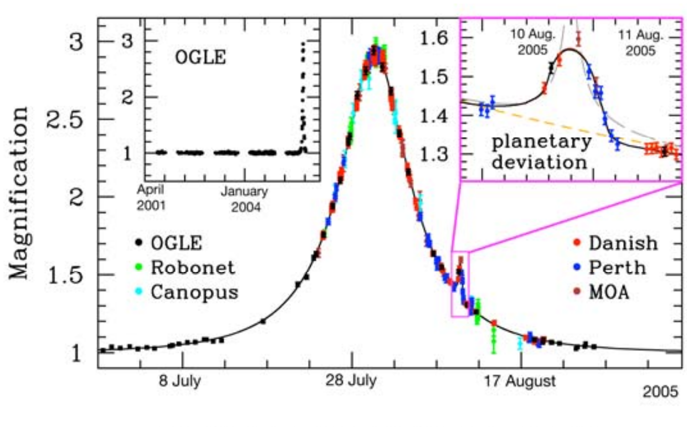
Discovery of a cool planet of 5.5 Earth masses through gravitational microlensing

J.-P. Beaulieu[1,4], D. P. Bennett[1,3,5], P. Fouqué[1,6], A. Williams[1,7], M. Dominik[1,8], U. G. Jørgensen[1,9], D. Kubas[1,10], A. Cassan[1,4], C. Coutures[1,11], J. Greenhill[1,12], K. Hill[1,12], J. Menzies[1,13], P. D. Sackett[1,14], M. Albrow[1,15], S. Brillant[1,10], J. A. R. Caldwell[1,16], J. J. Calitz[1,17], K. H. Cook[1,18], E. Corrales[1,4], M. Desort[1,4], S. Dieters[1,12], D. Dominis[1,19], J. Donatowicz[1,20], M. Hoffman[1,19], S. Kane[1,21], J.-B. Marquette[1,4], R. Martin[1,7], P. Meintjes[1,17], K. Pollard[1,15], K. Sahu[1,22], C. Vinter[1,9], J. Wambsganss[1,23], K. Woller[1,9], K. Horne[1,8], I. Steele[1,24], D. M. Bramich[1,8,24], M. Burgdorf[1,24], C. Snodgrass[1,25], M. Bode[1,24], A. Udalski[2,26], M. K. Szymański[2,26], M. Kubiak[2,26], T. Więckowski[2,26], G. Pietrzyński[2,26,27], I. Soszyński[2,26,27], O. Szewczyk[2,26], Ł. Wyrzykowski[2,26,28], B. Paczyński[2,29], F. Abe[3,30], I. A. Bond[3,31], T. R. Britton[3,15,32], A. C. Gilmore[3,15], J. B. Hearnshaw[3,15], Y. Itow[3,30], K. Kamiya[3,30], P. M. Kilmartin[3,15], A. V. Korpela[3,33], K. Masuda[3,30], Y. Matsubara[3,30], M. Motomura[3,30], Y. Muraki[3,30], S. Nakamura[3,30], C. Okada[3,30], K. Ohnishi[3,34], N. J. Rattenbury[3,28], T. Sako[3,30], S. Sato[3,35], M. Sasaki[3,30], T. Sekiguchi[3,30], D. J. Sullivan[3,33], P. J. Tristram[3,32], P. C. M. Yock[3,32] & T. Yoshioka[3,30]

In the favoured core-accretion model of formation of planetary systems, solid planetesimals accumulate to build up planetary cores, which then accrete nebular gas if they are sufficiently massive. Around M-dwarf stars (the most common stars in our Galaxy), this model favours the formation of Earth-mass ($M_⊕$) to Neptune-mass planets with orbital radii of 1 to 10 astronomical units (AU), which is consistent with the small number of gas giant planets known to orbit M-dwarf host stars[1–4]. More than 170

Gravitational microlensing events can reveal extrasolar planets orbiting the foreground lens stars if the light curves are measured frequently enough to characterize planetary light curve deviations with features lasting a few hours[6–9]. Microlensing is most sensitive to planets in Earth-to-Jupiter-like orbits with semi-major axes in the range 1–5 AU. The sensitivity of the microlensing method to low-mass planets is restricted by the finite angular size of the source stars[10,11], limiting detections to planets of a few $M_⊕$ for giant source stars, but allowing the detection of planets as small as $0.1 M_⊕$ for main-sequence source stars in the Galactic Bulge. The PLANET

OB05390



Light Curve of OGLE-2005-BLG-390

ESO PR Photo 03b/06 (January 25, 2006)

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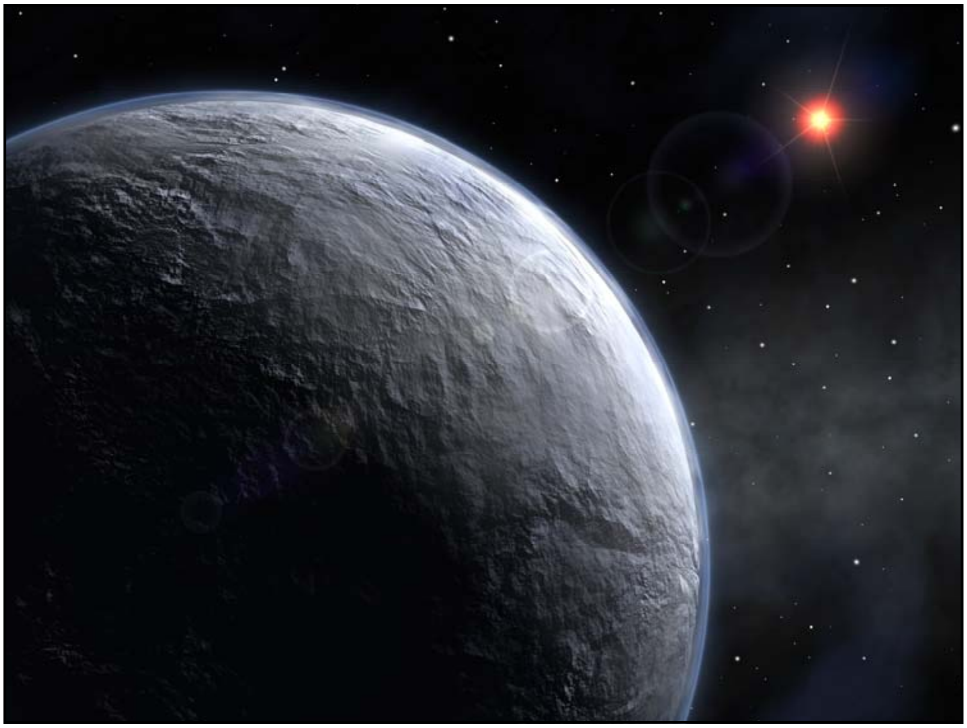

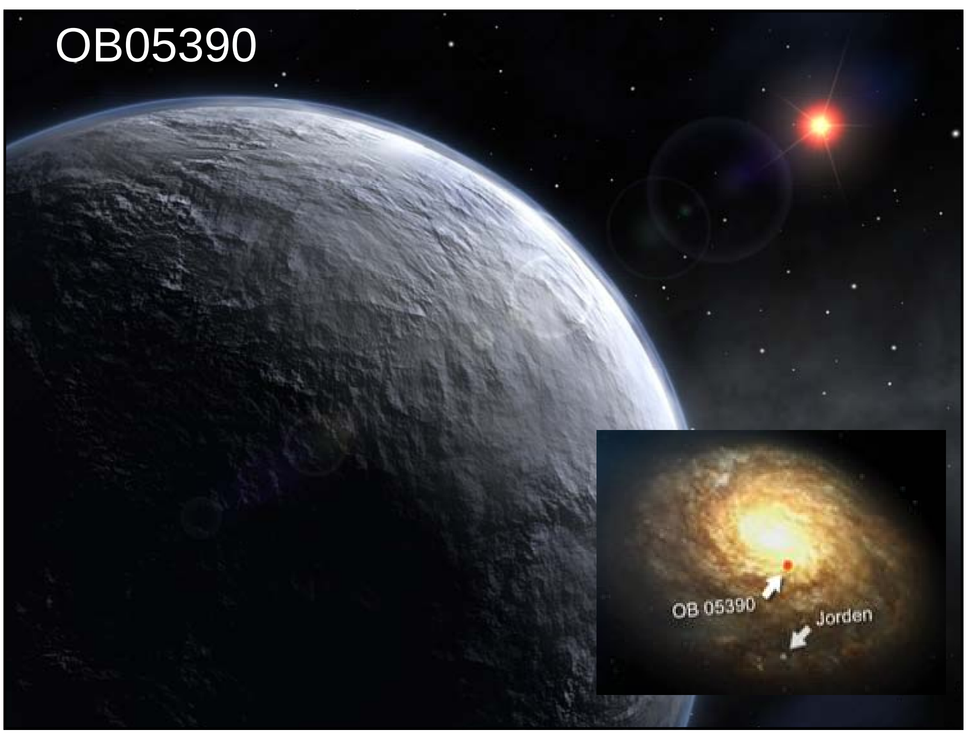
OB05390
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Jorden

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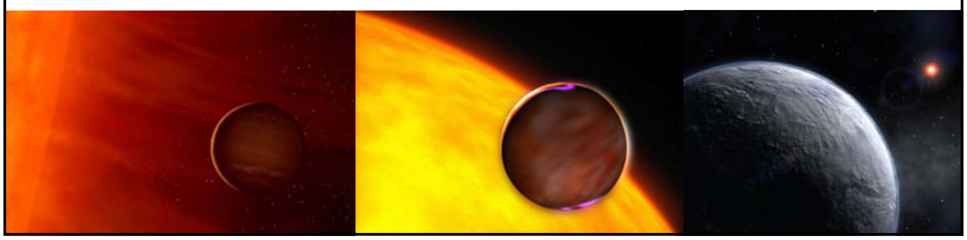

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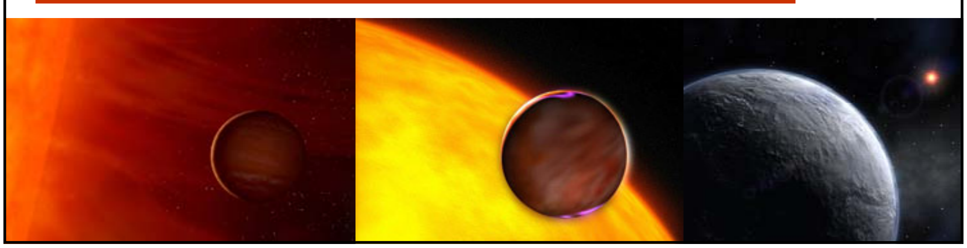
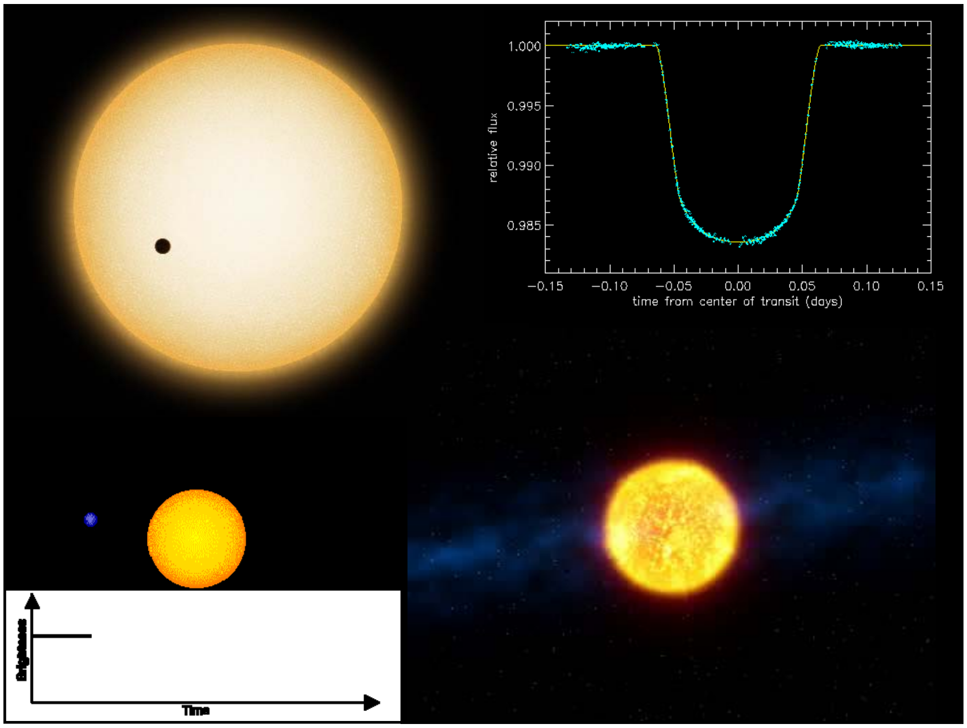
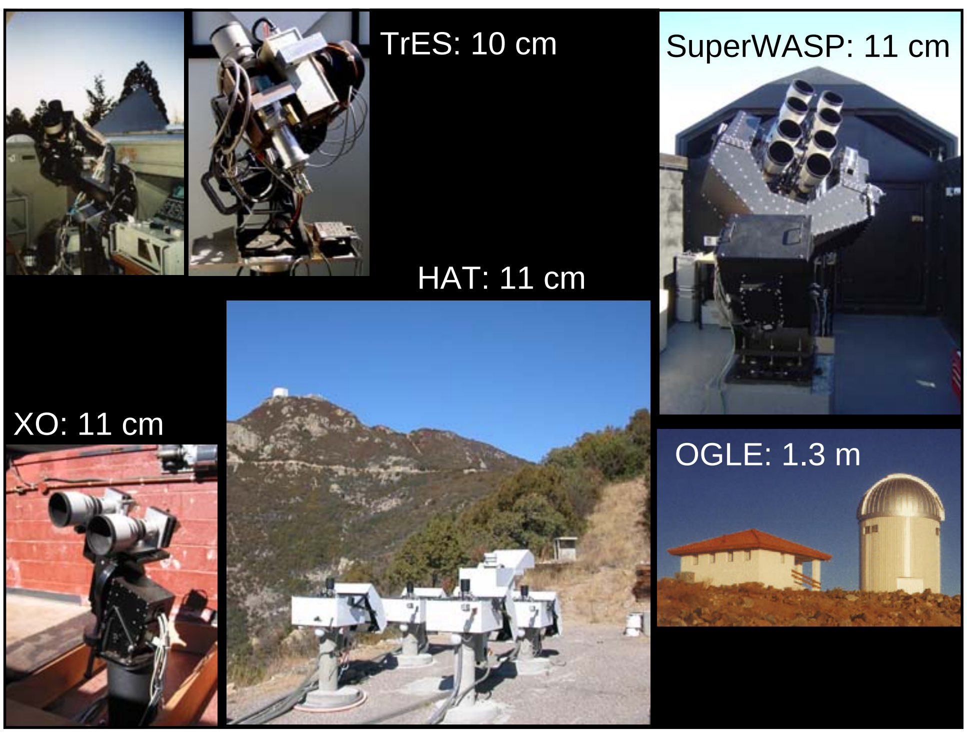
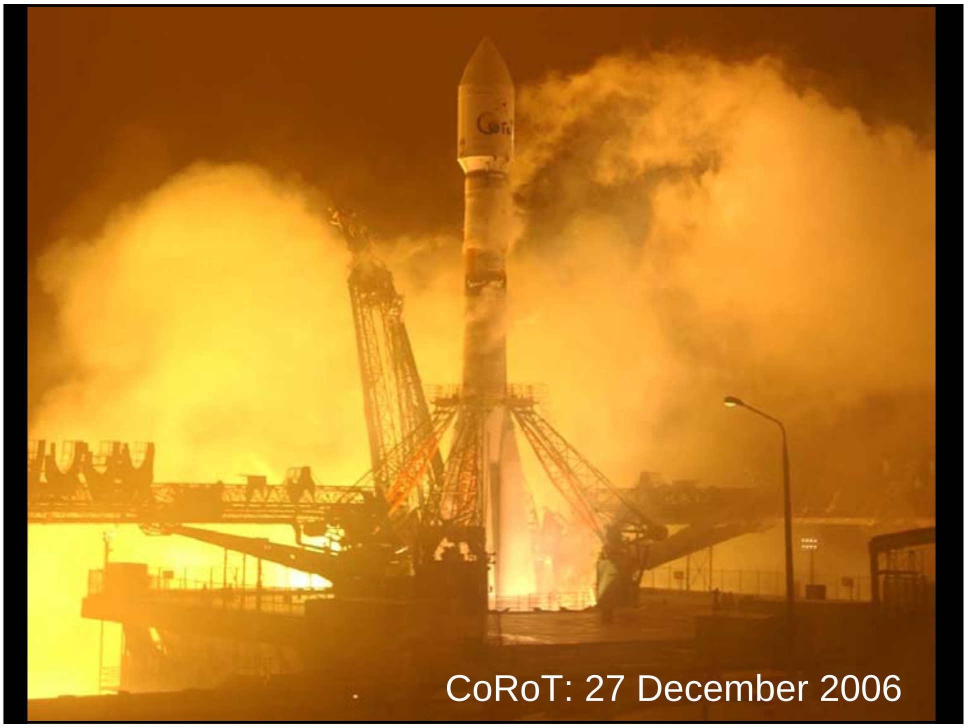
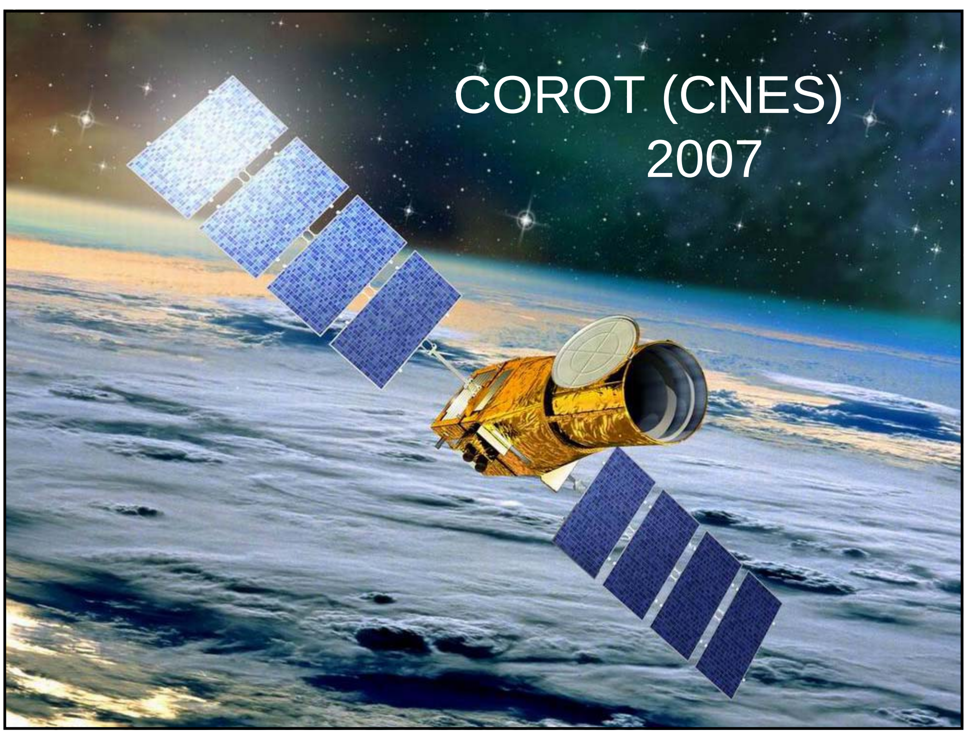
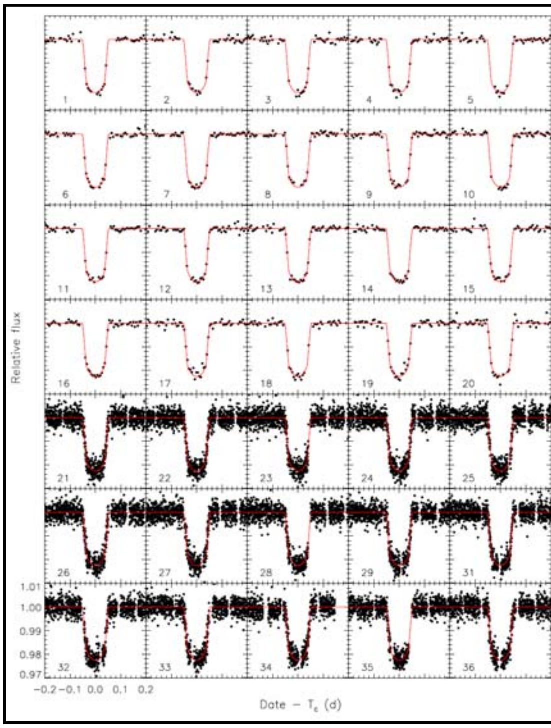


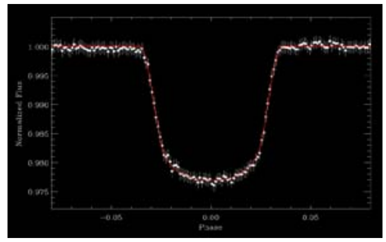

1.000
0.995
0.990
0.985
relative flux
−0.15 −0.10 −0.05 0.00 0.05 0.10 0.15
time from center of transit (days)
Brightness
Time


TrES: 10 cm
SuperWASP: 11 cm
HAT: 11 cm
XO: 11 cm
OGLE: 1.3 m

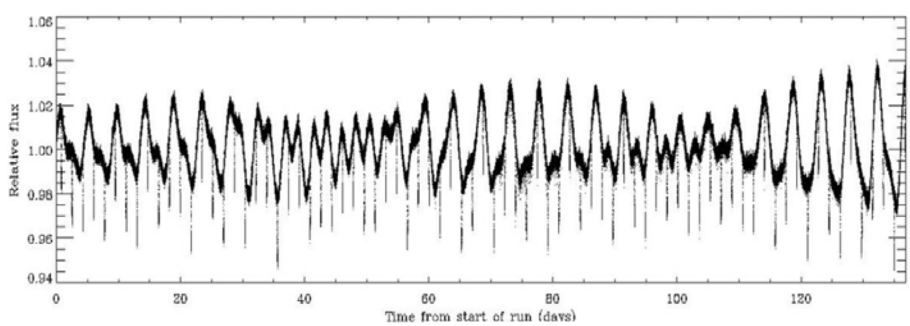

CoRoT: 27 December 2006


COROT (CNES)
2007

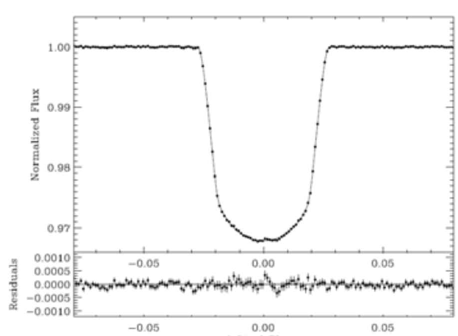


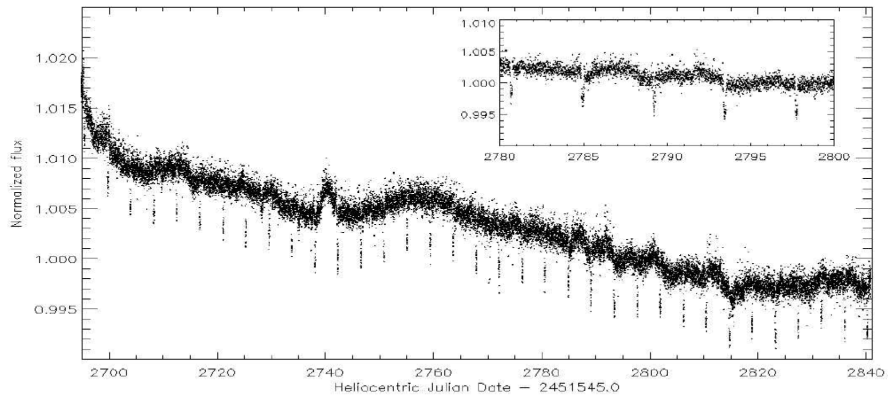


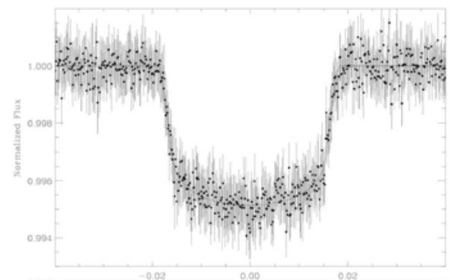
CoRoT-1



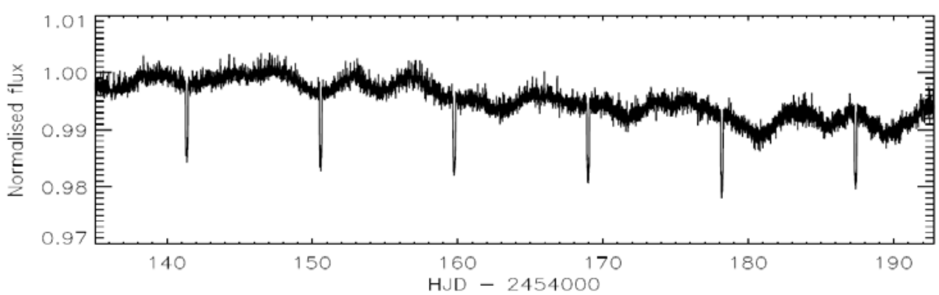
CoRoT-2



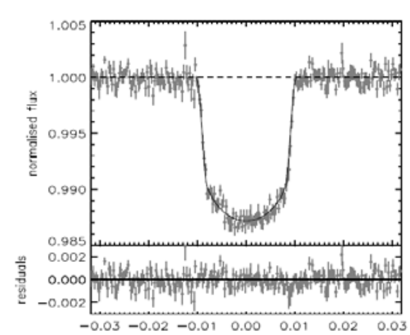


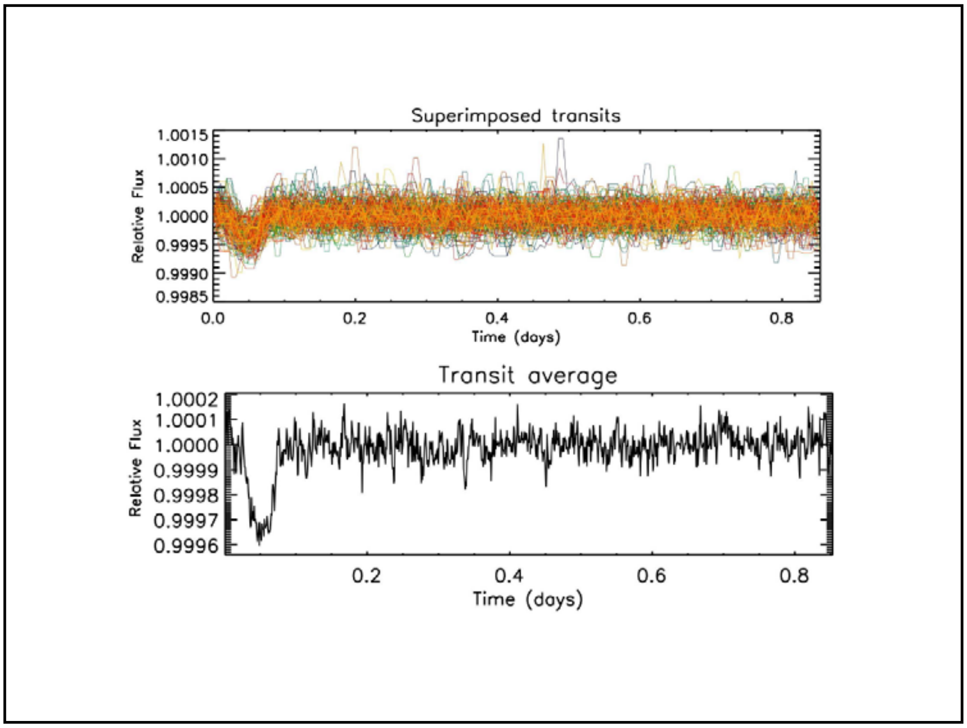


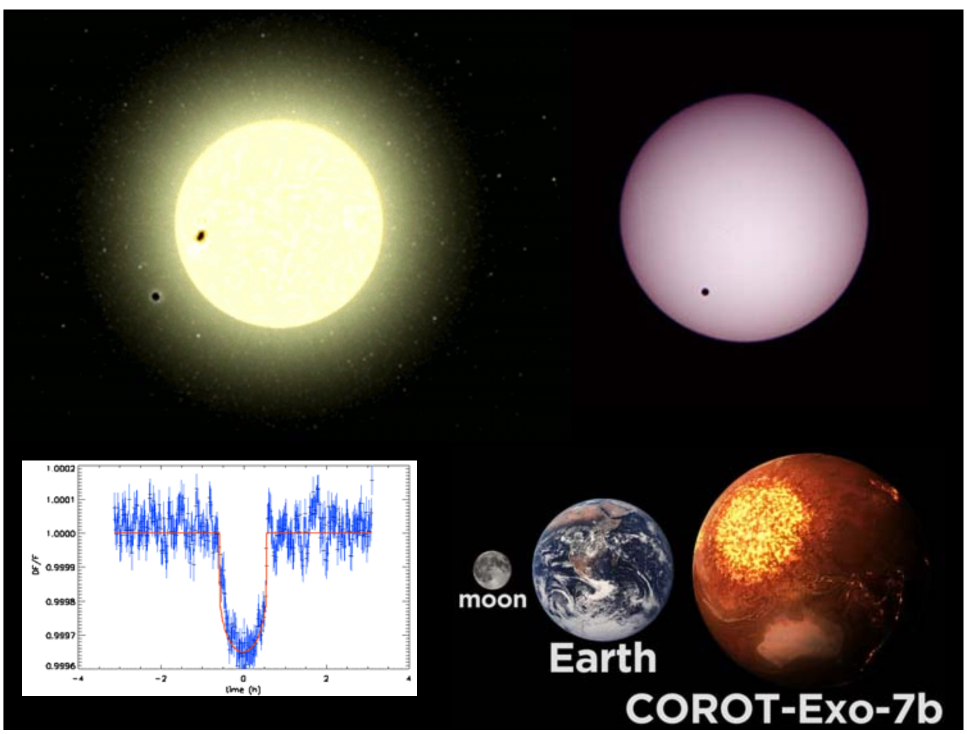
CoRoT-3

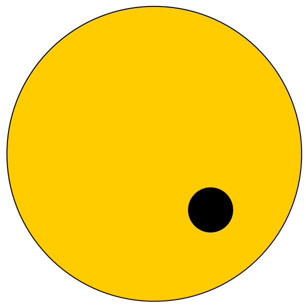


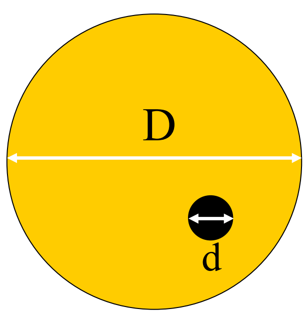
CoRoT-4



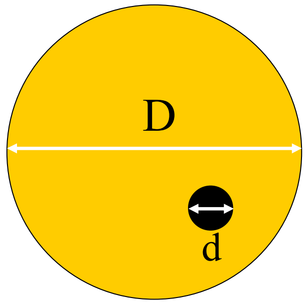

Superimposed transits
Relative Flux
Time (days)
Transit average
Relative Flux
Time (days)


moon
Earth
COROT-Exo-7b



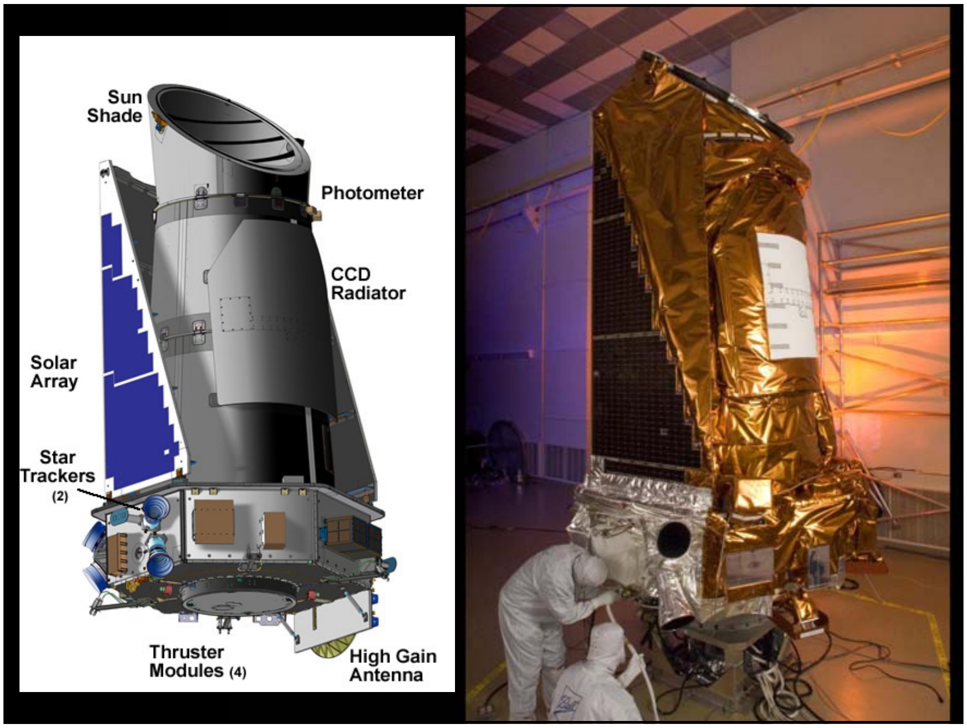


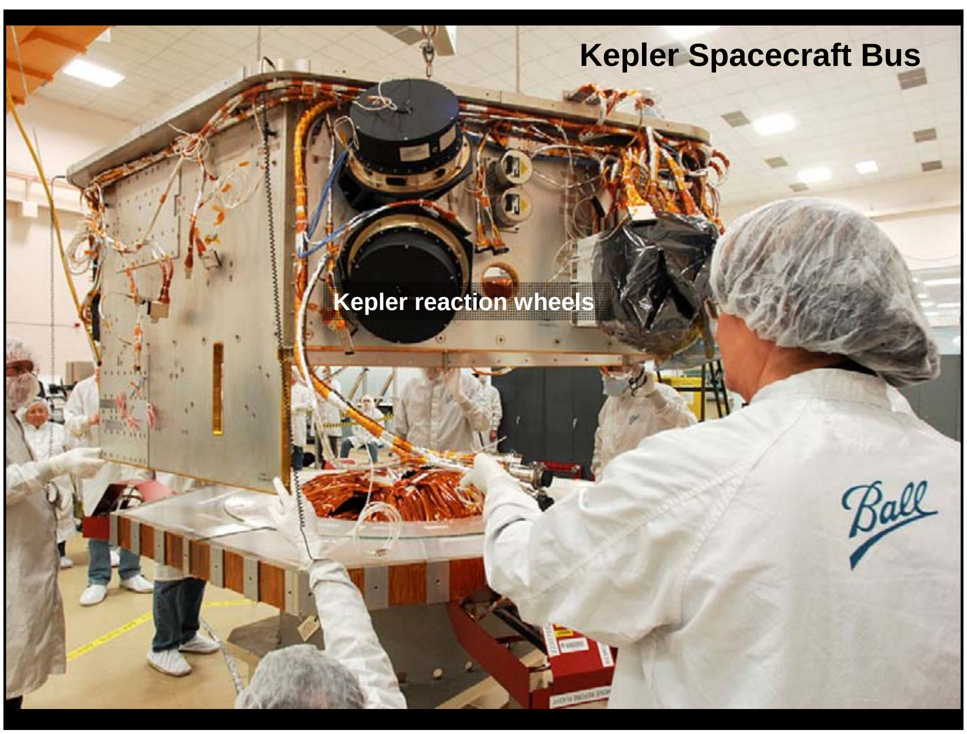
$$\frac{a}{A} = \frac{\pi \cdot r^2}{\pi \cdot R^2} = \frac{d^2}{D^2} = \left(\frac{d}{D}\right)^2$$



$$\frac{a}{A} = \frac{\pi \cdot r^2}{\pi \cdot R^2} = \frac{d^2}{D^2} = \left(\frac{d}{D}\right)^2$$

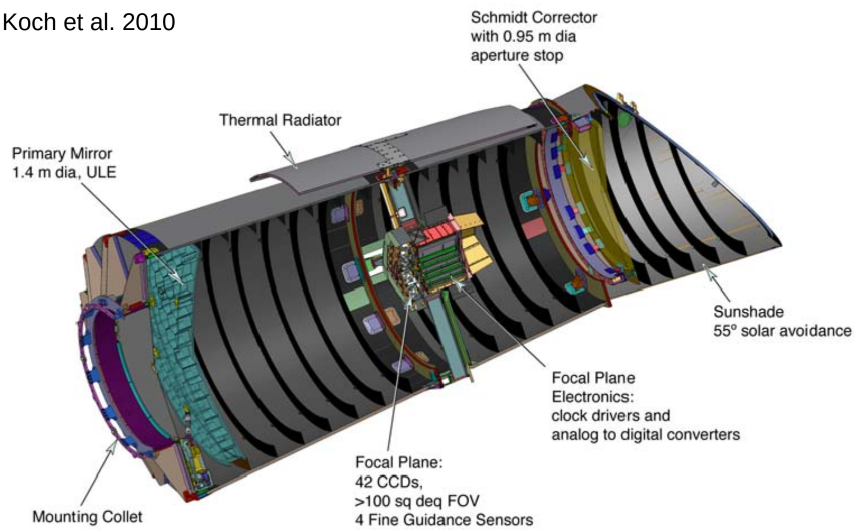
Jupiter:	1 %
Uranus:	0,1 %
Jorden:	0,01 %

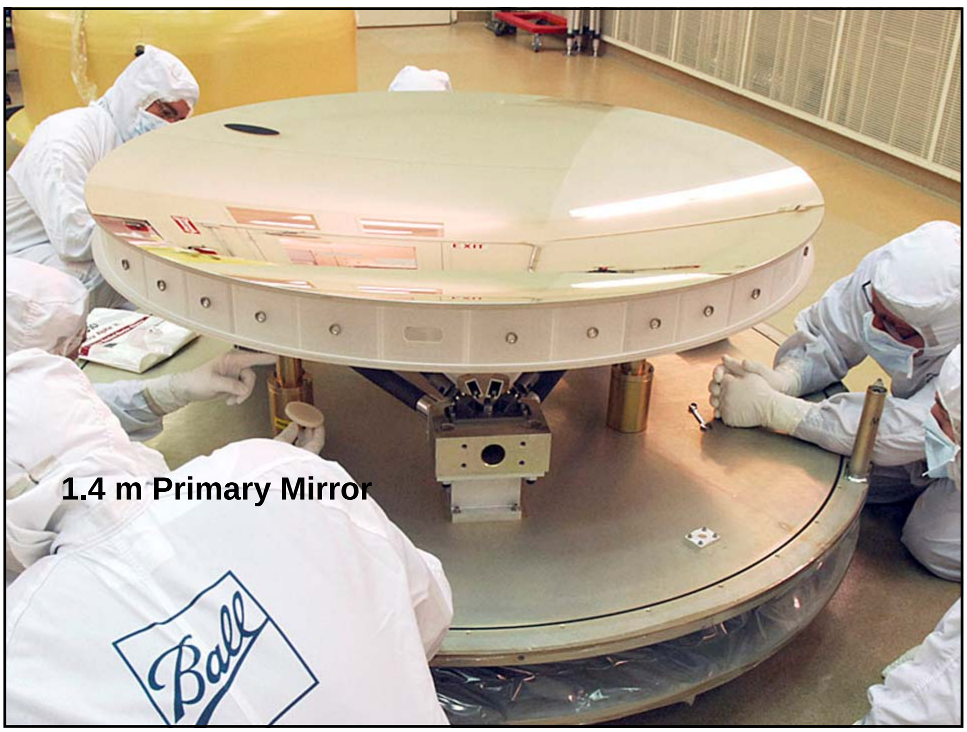

Sun Shade
Photometer
CCD Radiator
Solar Array
Star Trackers (2)
Thruster Modules (4)
High Gain Antenna


Kepler Spacecraft Bus
Kepler reaction wheels
Ball

Kepler Photometer

Koch et al. 2010

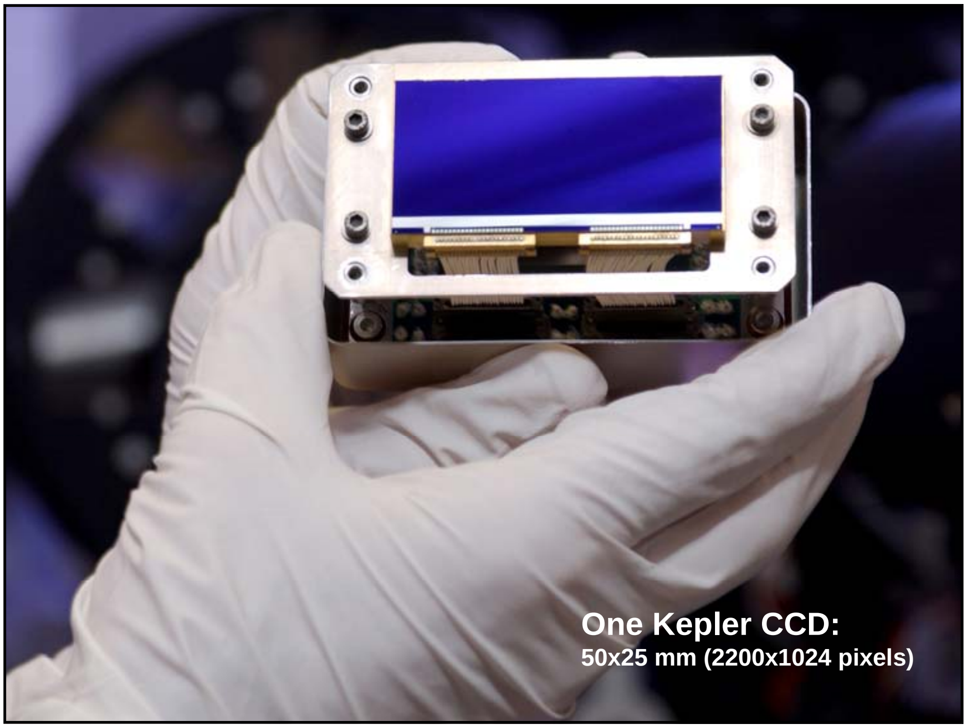




1.4 m Primary Mirror

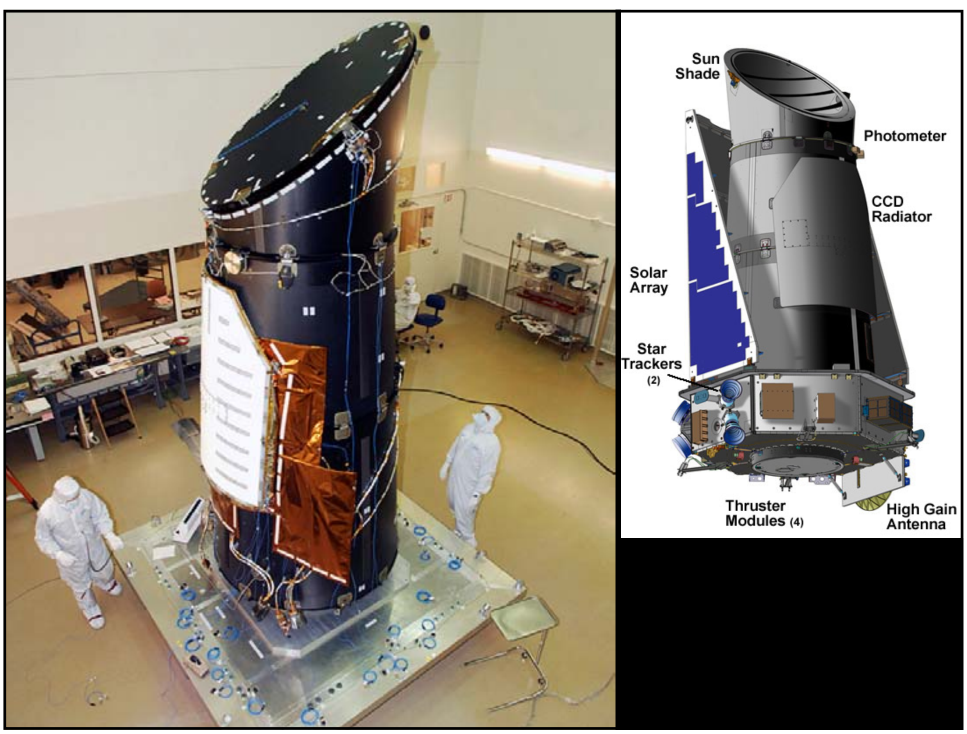

95 cm Schmidt Corrector


95 cm Schmidt Corrector

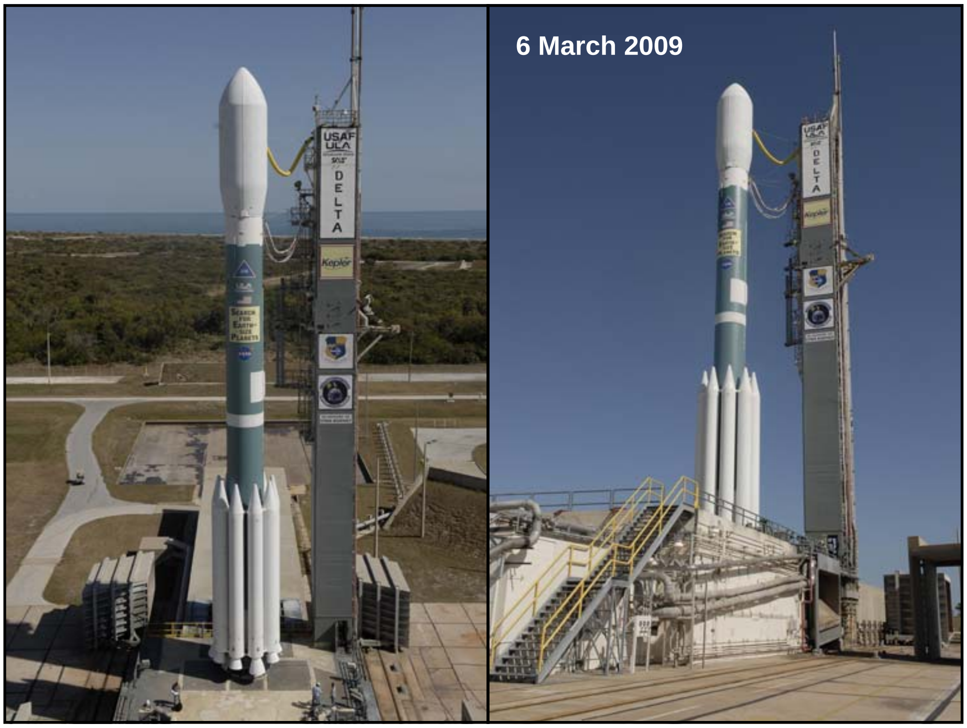

One Kepler CCD:
50x25 mm (2200x1024 pixels)

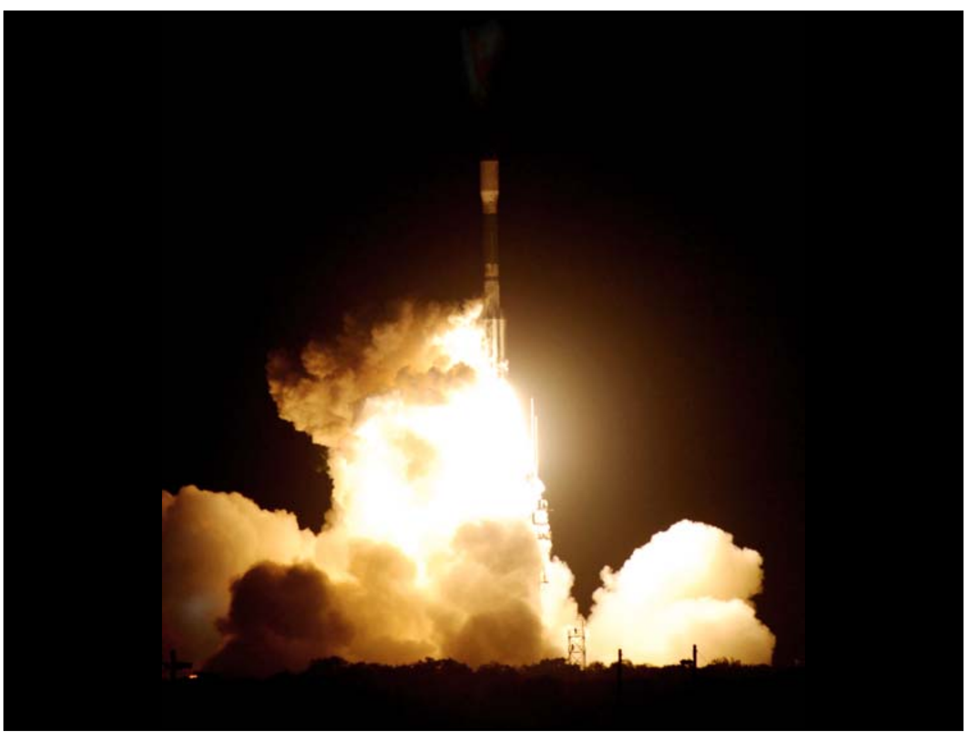

Focal Plane Assembly
42 CCDs with Field Flattener Lenses

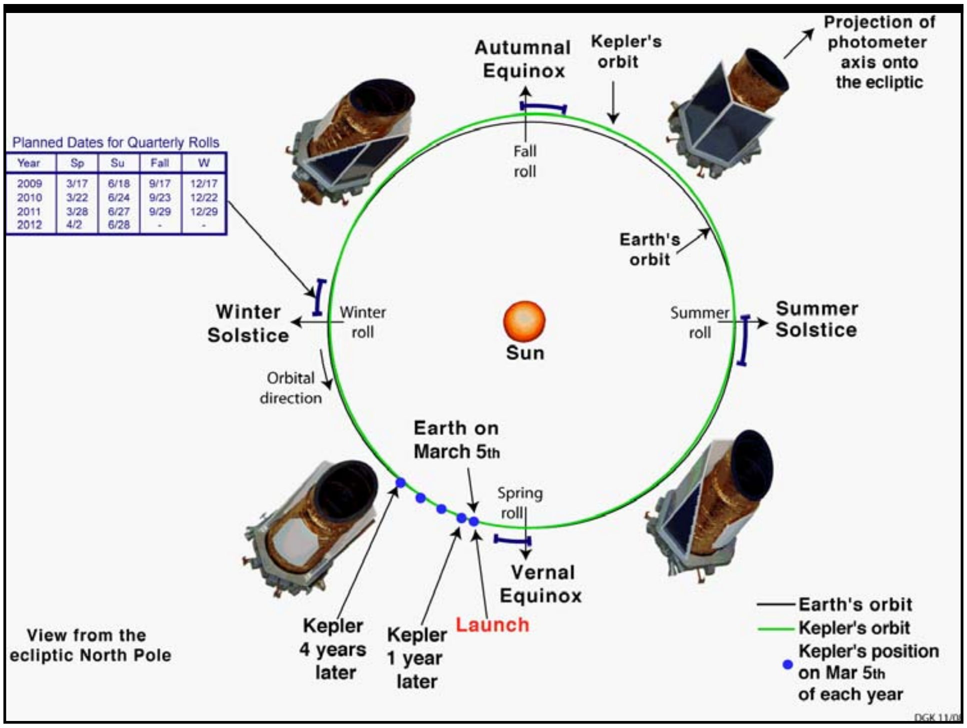

Focal Plane Assembly
42 CCDs with Field Flattener Lenses

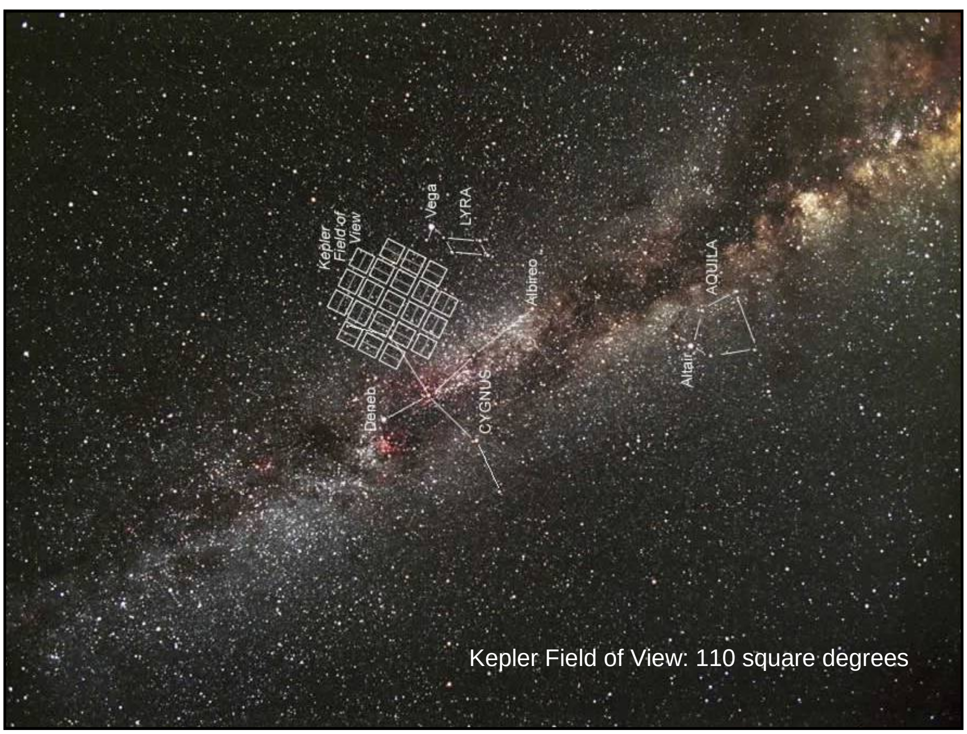

Sun Shade
Photometer
CCD Radiator
Solar Array
Star Trackers (2)
Thruster Modules (4)
High Gain Antenna

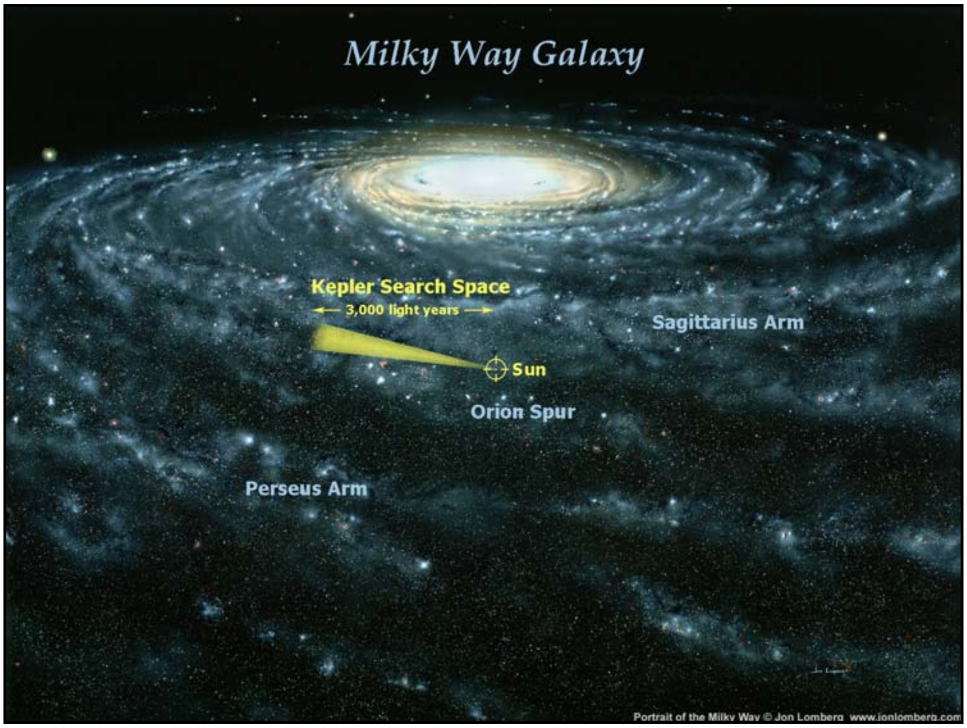
Cape Canaveral, SLC-17-B, October-December 2008, **DELTA 7925 STAGE 1**

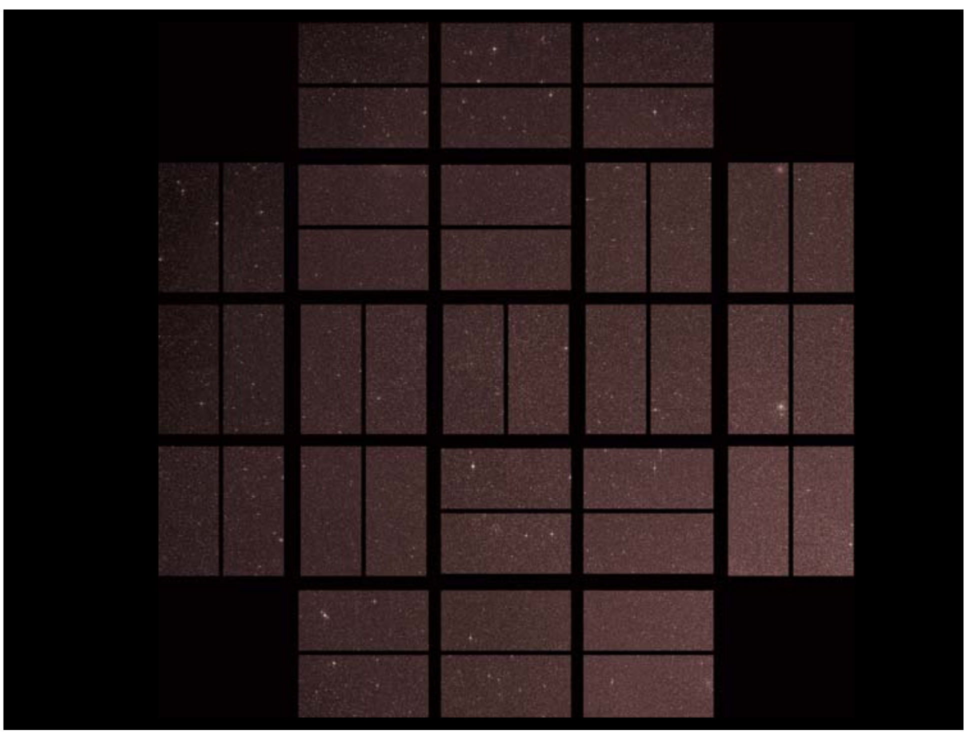

6 March 2009
USAF
ULA
DELTA
Kepler

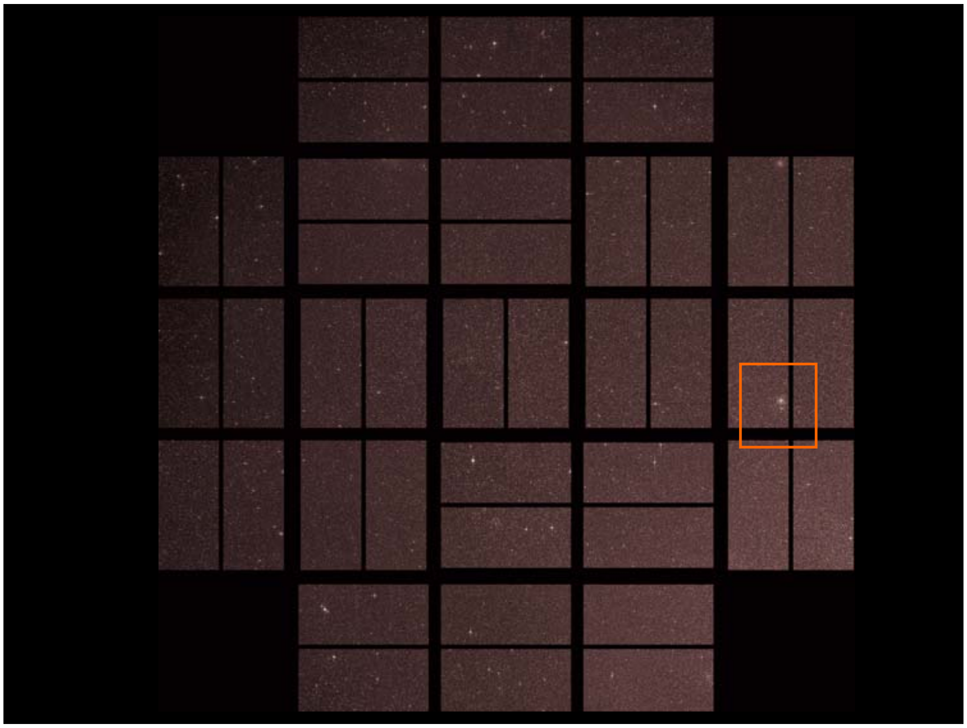


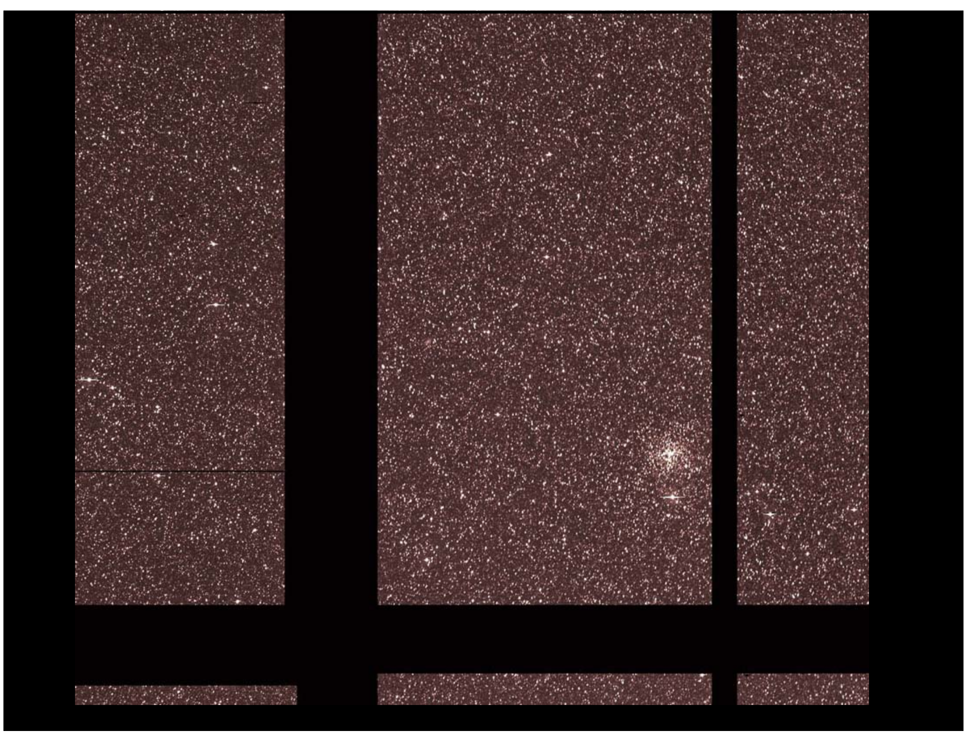

Planned Dates for Quarterly Rolls
Year | Sp | Su | Fall | W
2009 | 3/17 | 6/18 | 9/17 | 12/17
2010 | 3/22 | 6/24 | 9/23 | 12/22
2011 | 3/28 | 6/27 | 9/29 | 12/29
2012 | 4/2 | 6/28 | - | -
Autumnal Equinox
Kepler's orbit
Projection of photometer axis onto the ecliptic
Fall roll
Earth's orbit
Winter Solstice
Winter roll
Sun
Summer roll
Summer Solstice
Orbital direction
Earth on March 5th
Spring roll
Vernal Equinox
View from the ecliptic North Pole
Kepler 4 years later
Kepler 1 year later
Launch
Earth's orbit
Kepler's orbit
Kepler's position on Mar 5th of each year

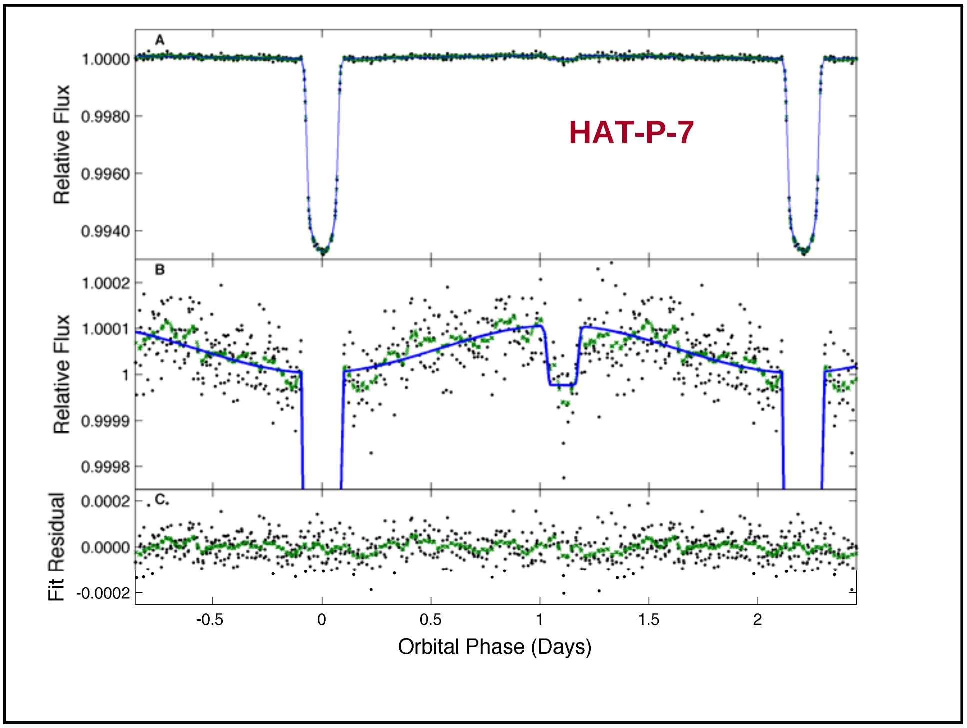

Kepler Field of View
Vega
LYRA
Albireo
AQUILA
Altair
Deneb
CYGNUS
Kepler Field of View: 110 square degrees

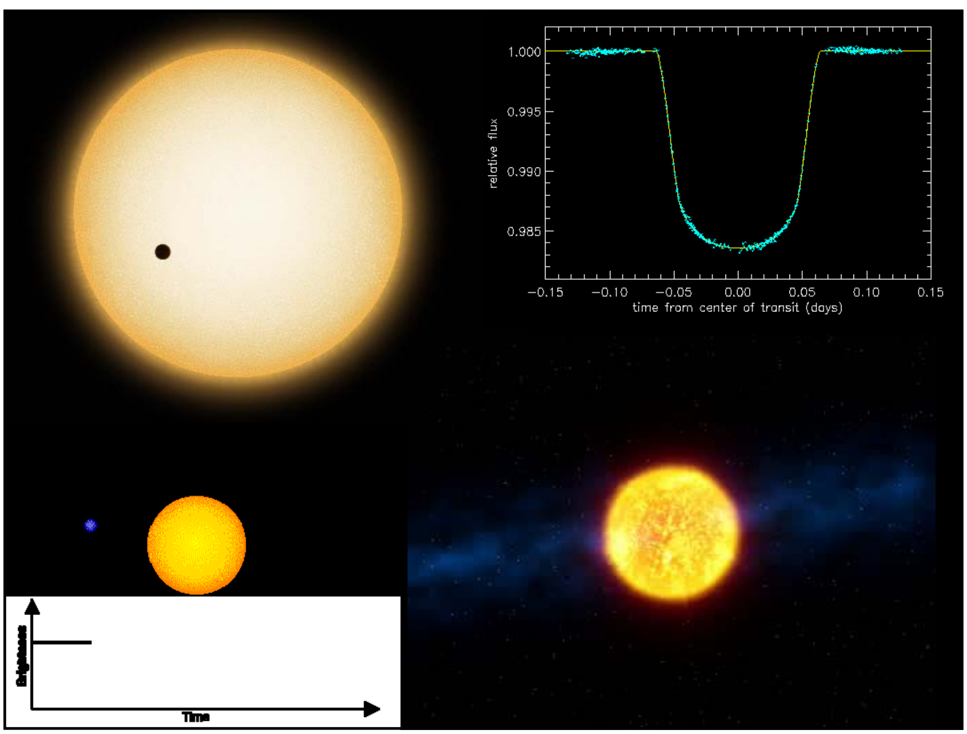

Milky Way Galaxy
Kepler Search Space
3,000 light years
Sagittarius Arm
Sun
Orion Spur
Perseus Arm
Portrait of the Milky Way © Jon Lomberg www.jonlomberg.com

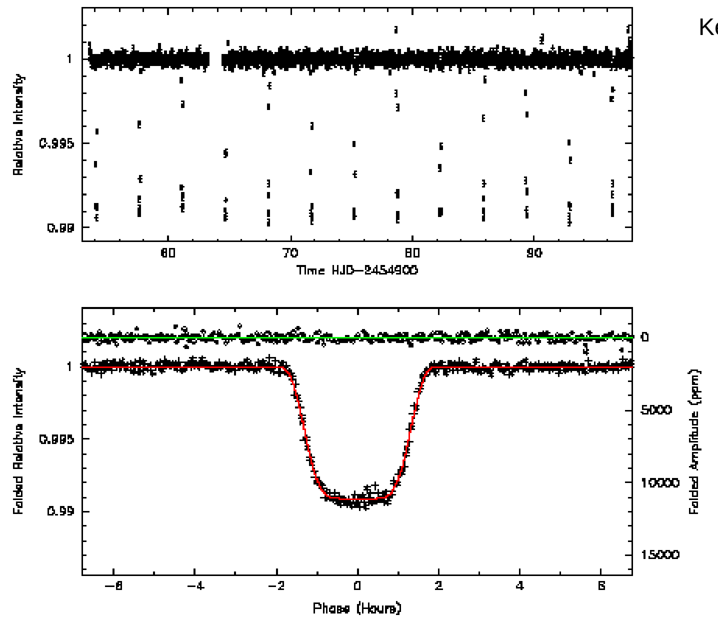




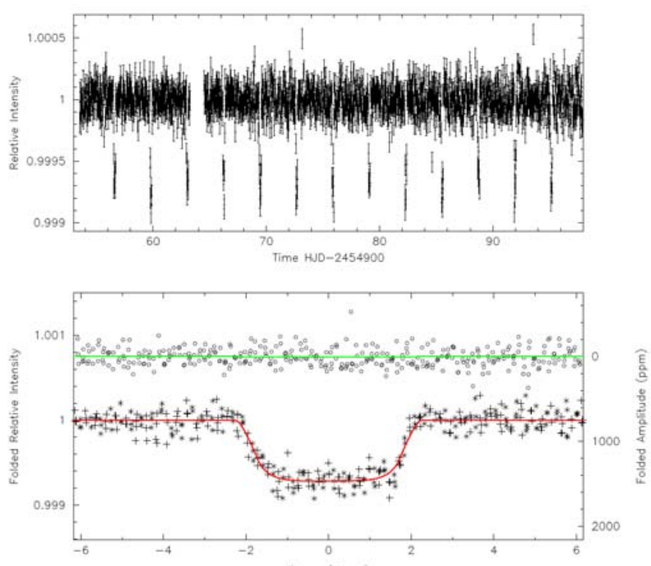



HAT-P-7
A
B
C
Relative Flux
Fit Residual
1.0000
0.9980
0.9960
0.9940
1.0002
1.0001
1
0.9999
0.9998
0.0002
0.0000
-0.0002
-0.5
0
0.5
1
1.5
2
Orbital Phase (Days)


relative flux
1.000
0.995
0.990
0.985
−0.15
−0.10
−0.05
0.00
0.05
0.10
0.15
time from center of transit (days)



Borucki et al. 2010: Kepler-4b




Kepler
A Search for Terrestrial Planets


51 Peg b
HD 189733 b
Findes der andre planeter som Jorden?
Gliese 581 c
V 391 Pegasi
OGLE-2005-BLG-390 b

Webpage…

http://astro.phys.au.dk/KASC/exoplanet

http://astro.phys.au.dk/~hans/exoplanet