Transiting Extra-Solar Planets

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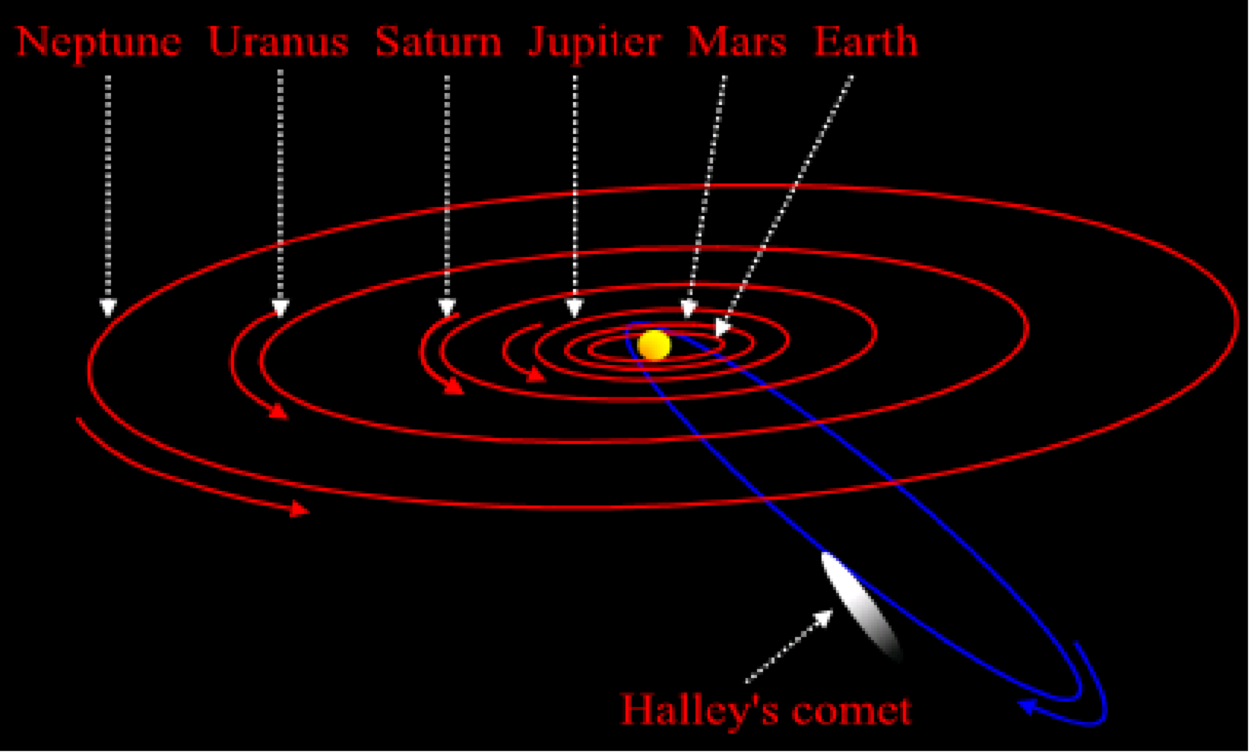
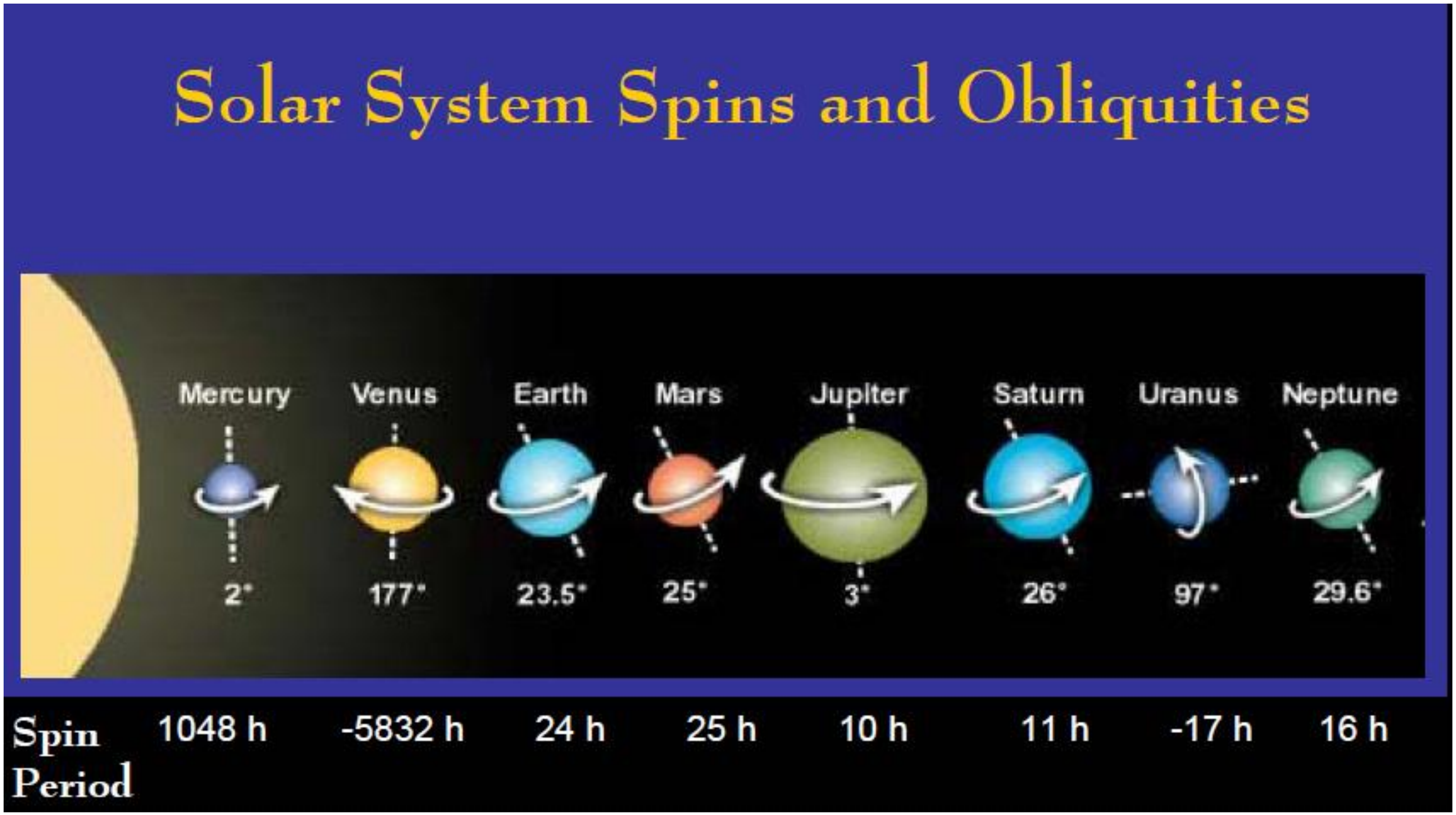
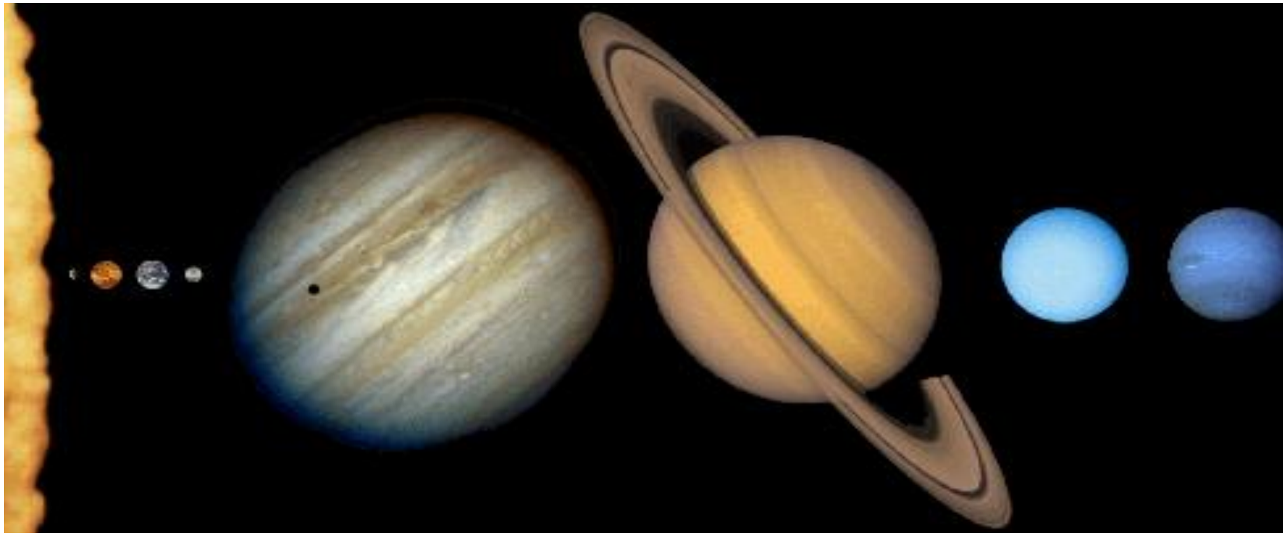
Dec 2011

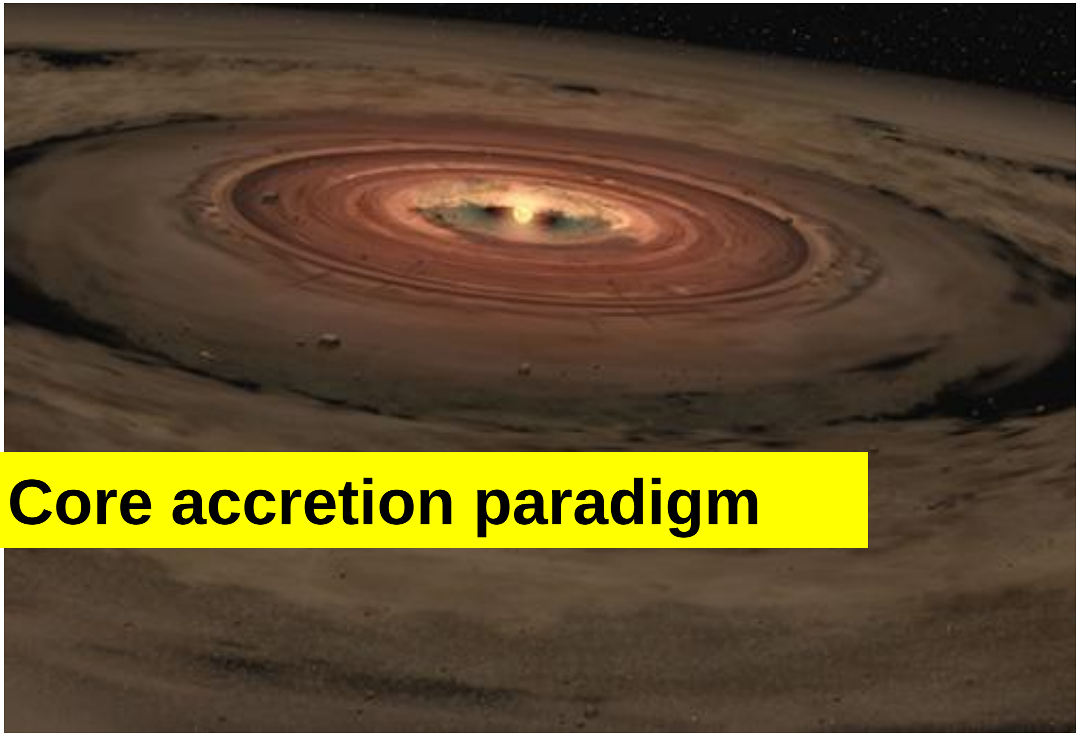


In the solar system:

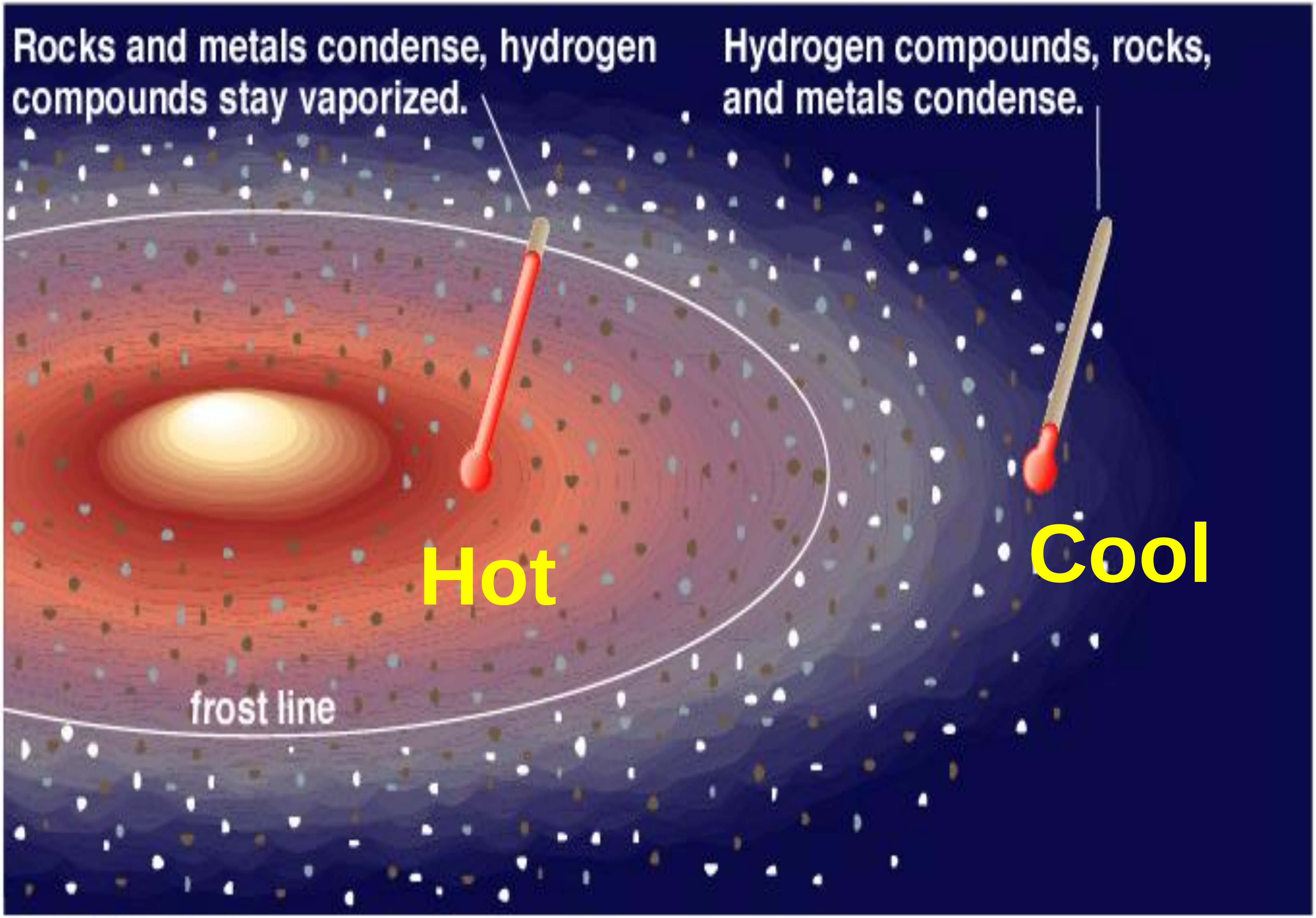
- Giant planets far away
- Circular orbits
- Planetary orbits aligned with the Solar spin

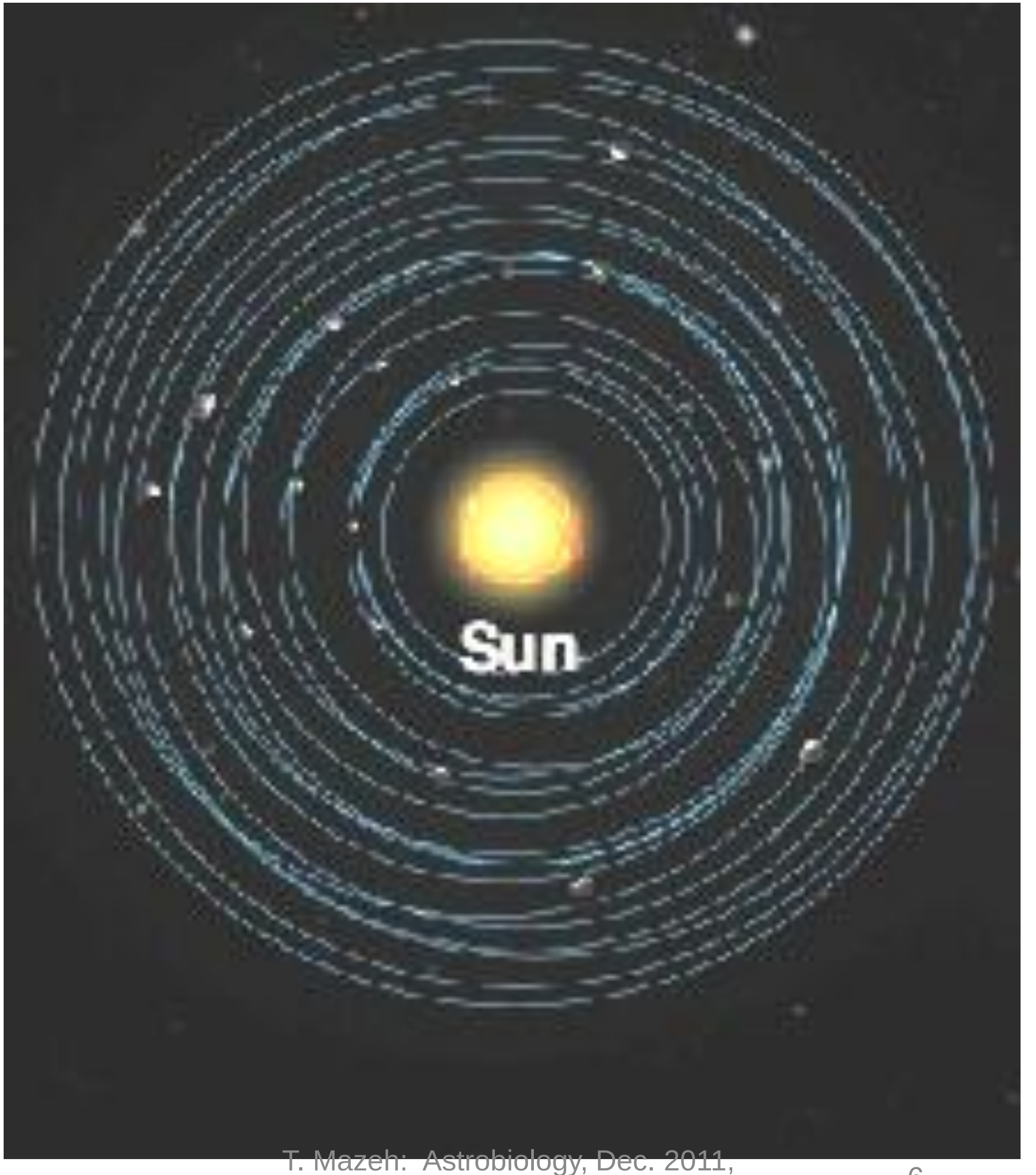

Solar System Spins and Obliquities
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
2°
177°
23.5°
25°
3°
26°
97°
29.6°
Spin Period
1048 h
-5832 h
24 h
25 h
10 h
11 h
-17 h
16 h





Core accretion paradigm

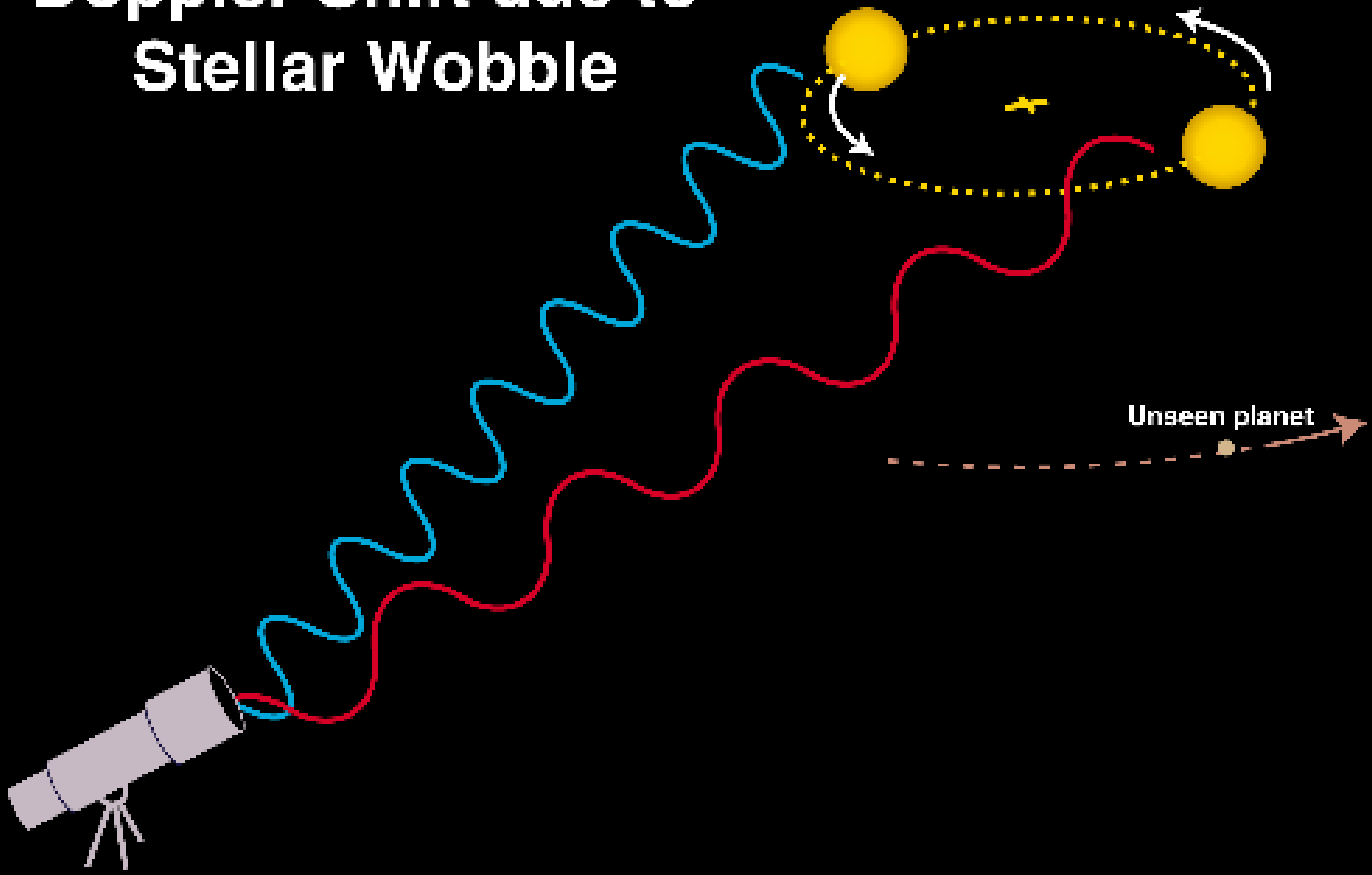

Rocks and metals condense, hydrogen compounds stay vaporized.
Hydrogen compounds, rocks, and metals condense.
Hot
Cool
frost line

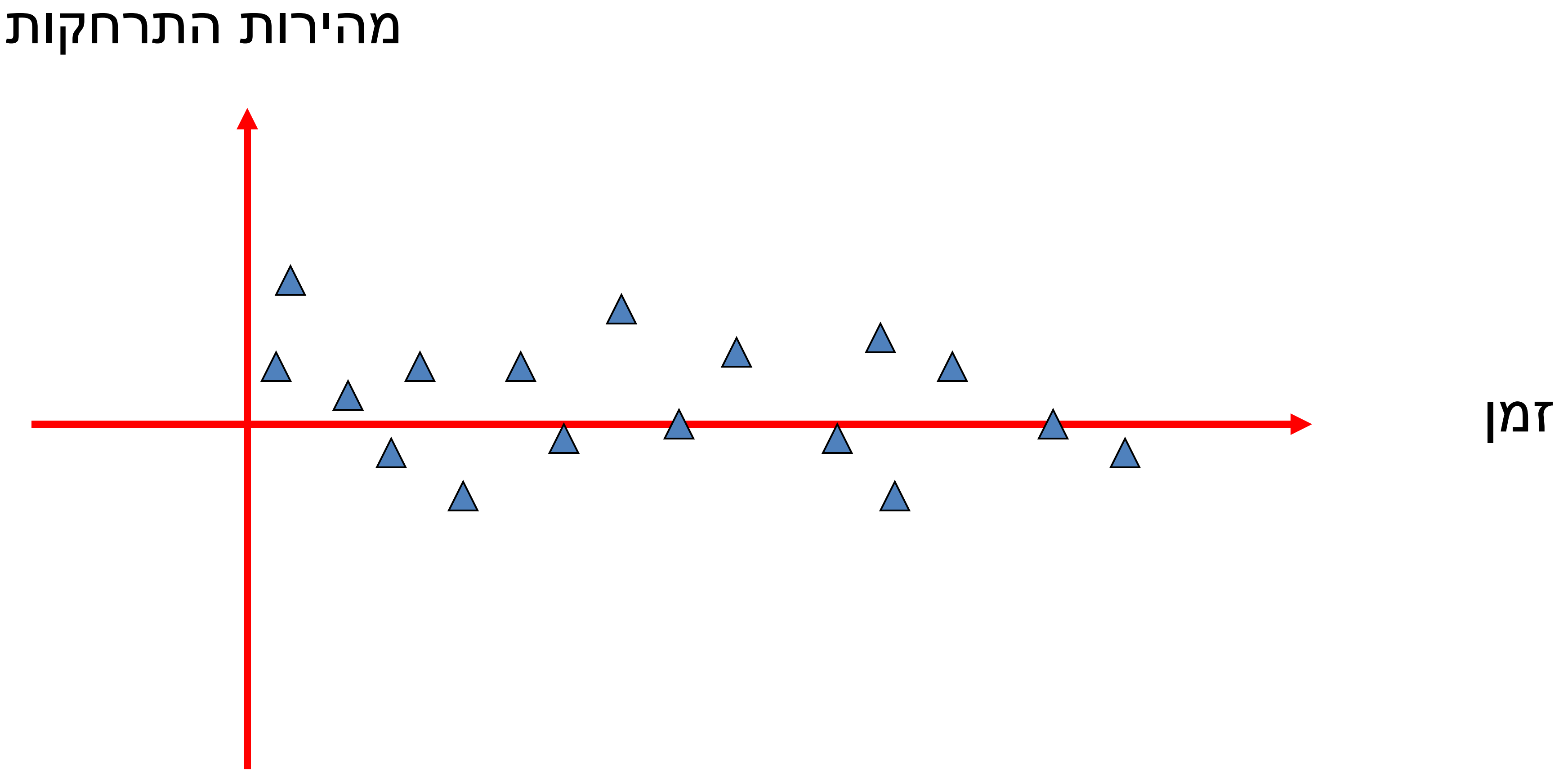

Sun

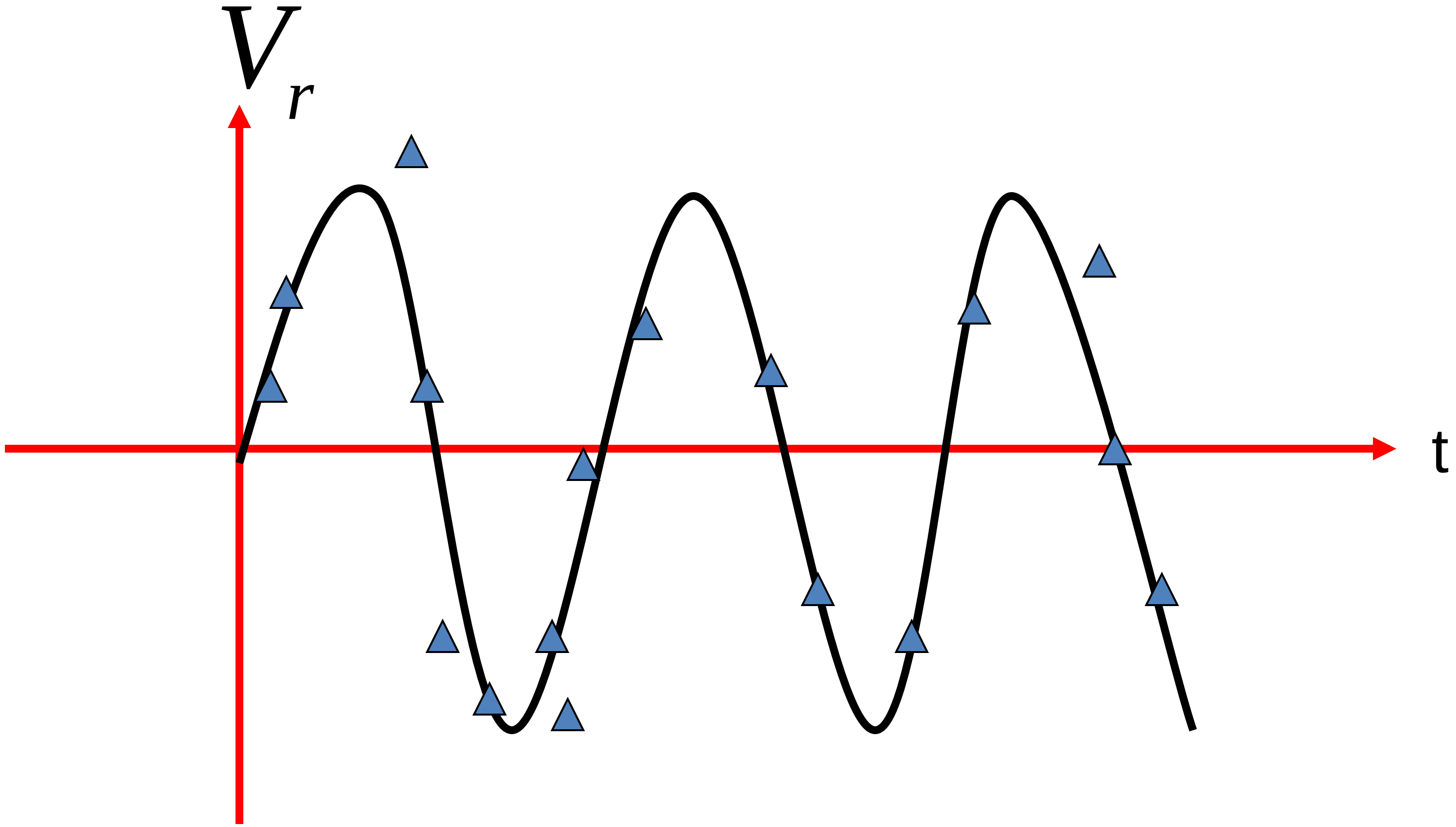

Sun


Sun

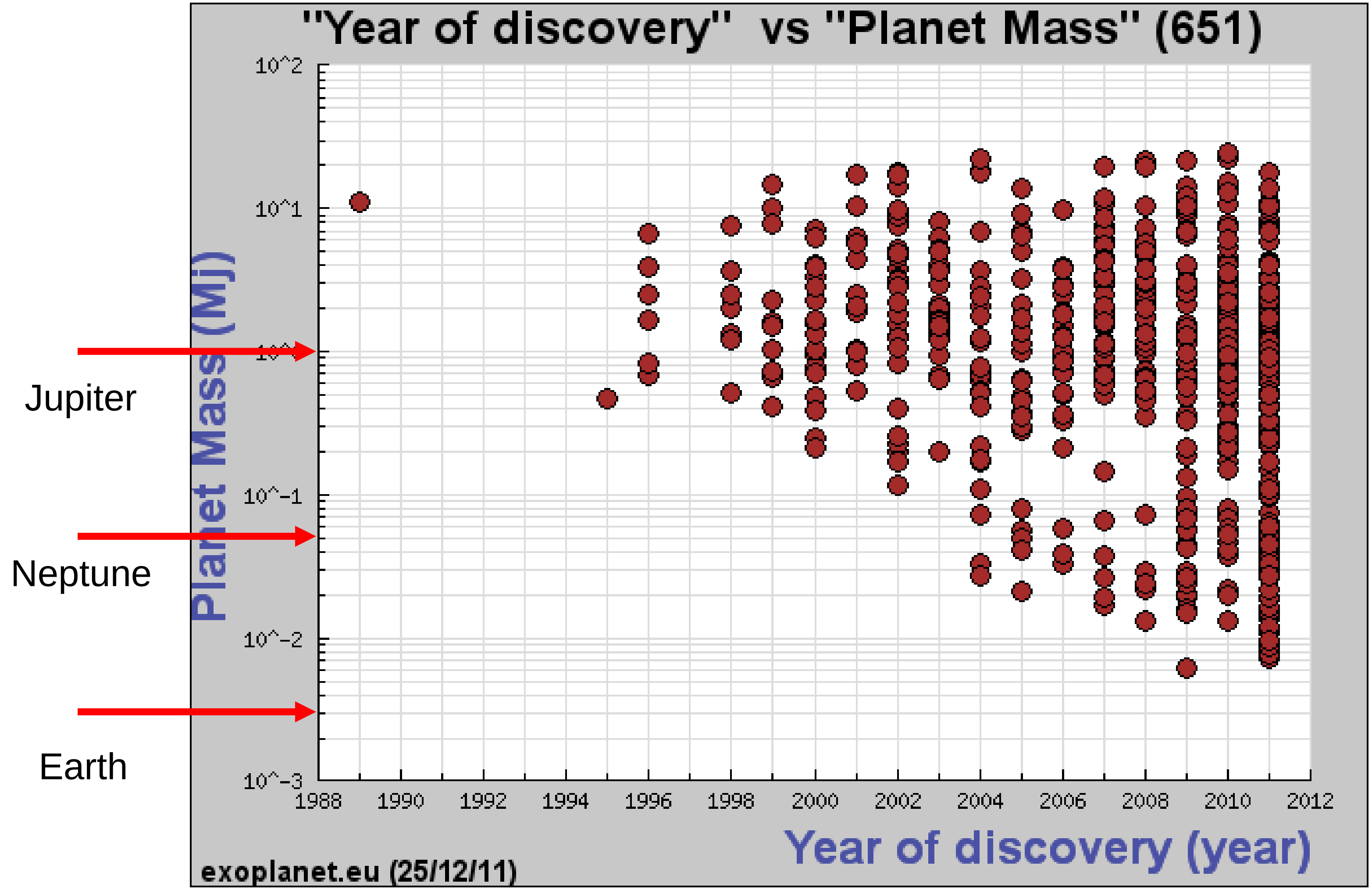
Doppler Shift due to Stellar Wobble



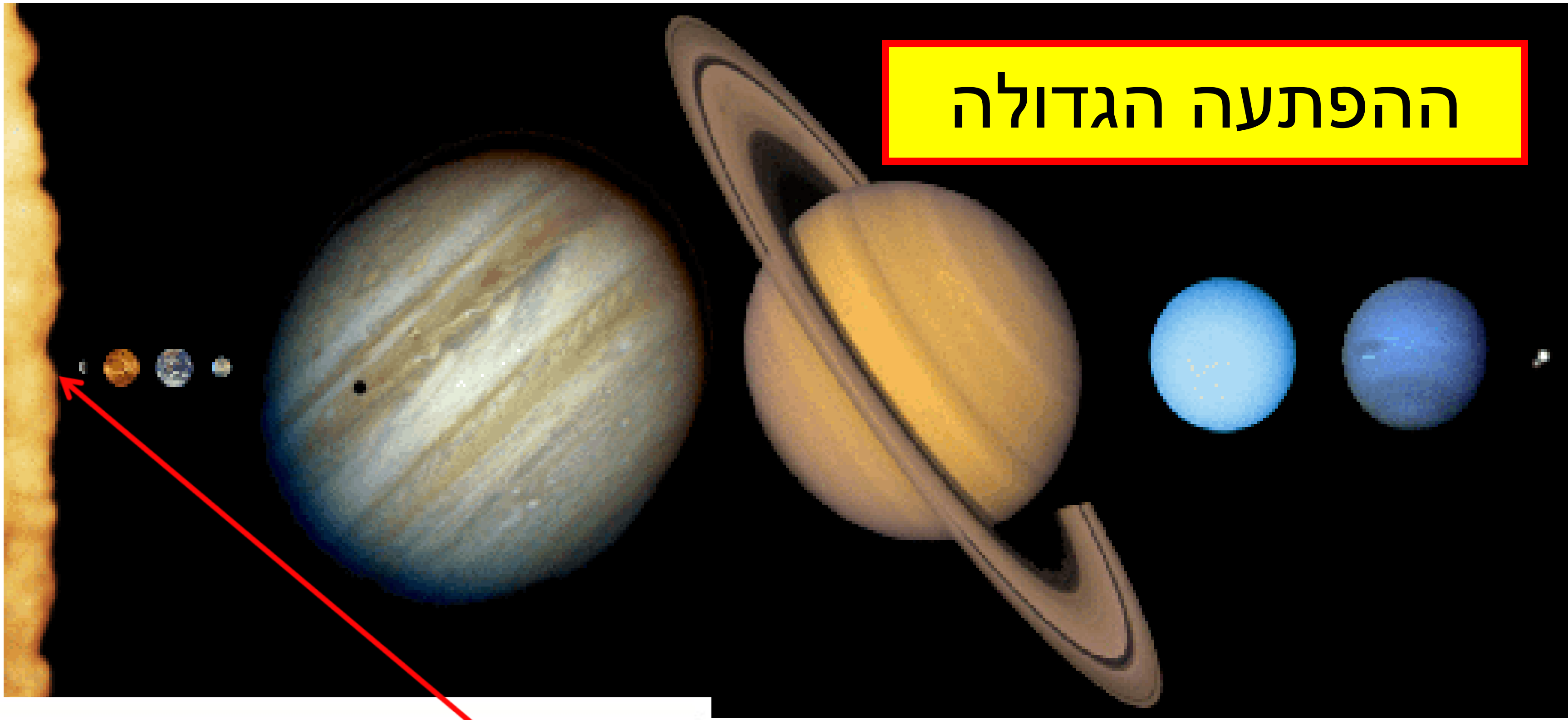

מהירות התרחקות
זמן

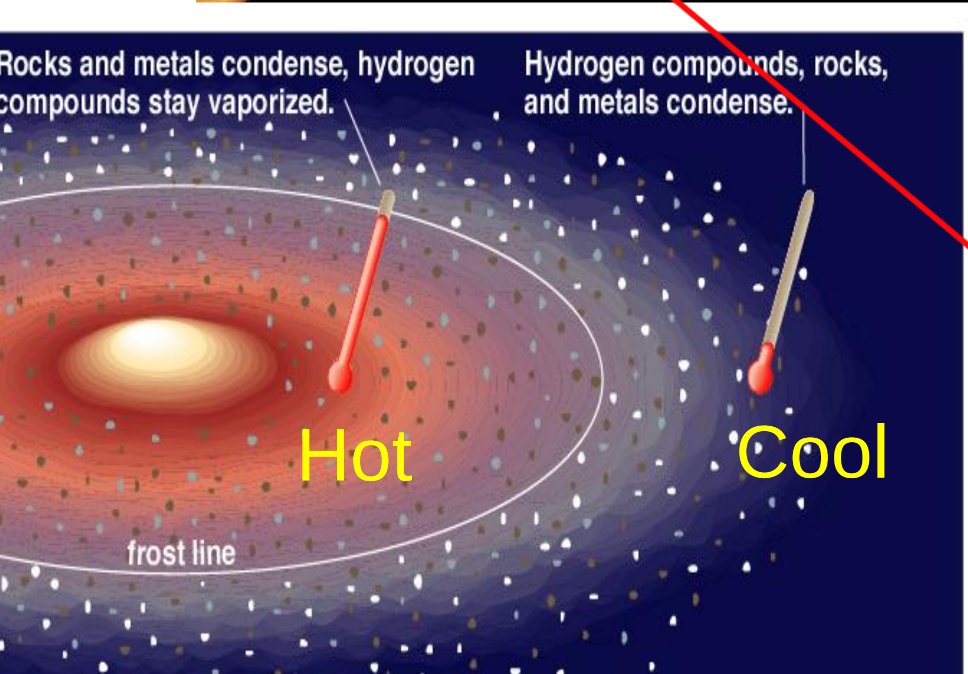

V_r
t

Extra-solar planets:



ההפתעה הגדולה

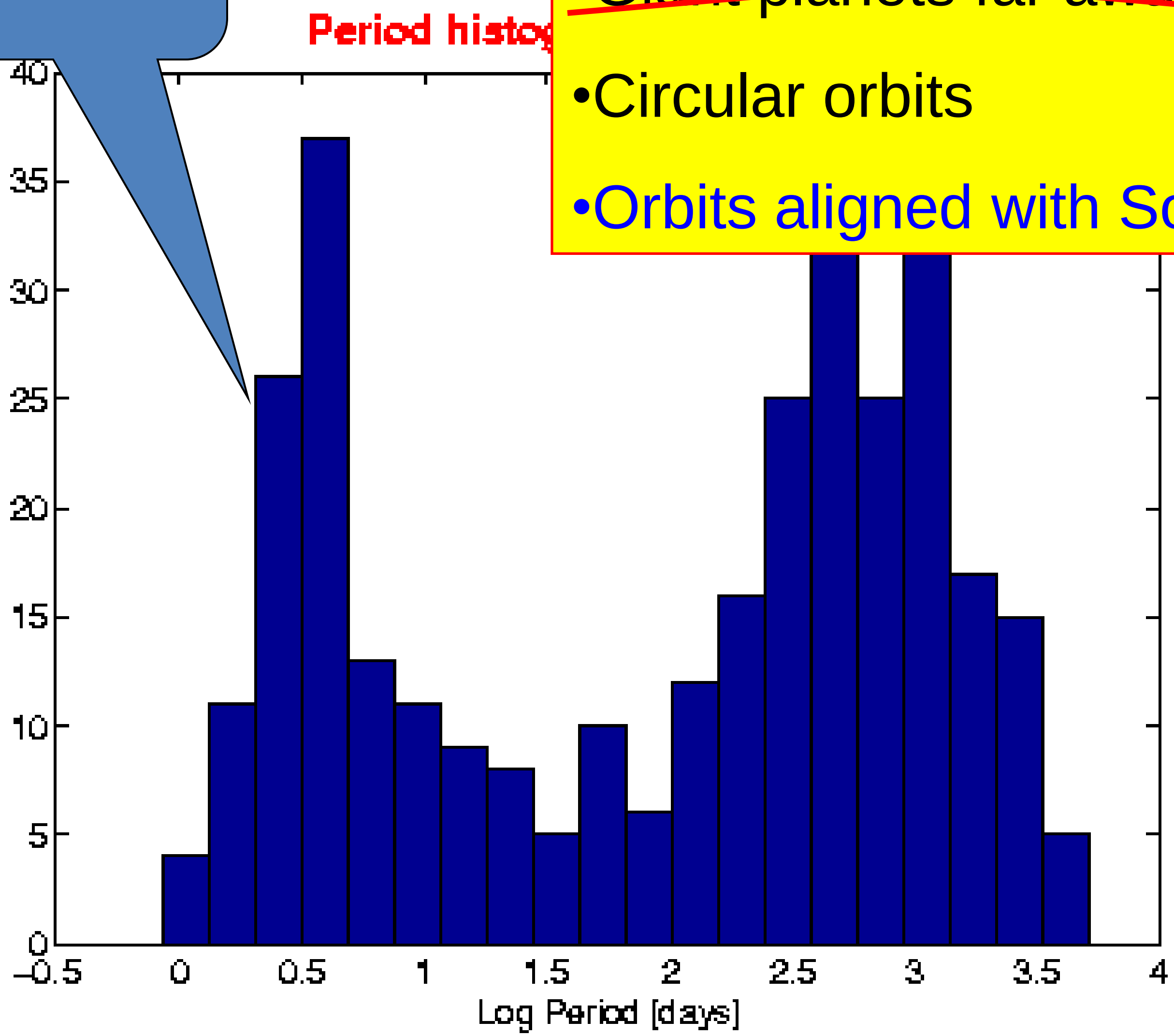




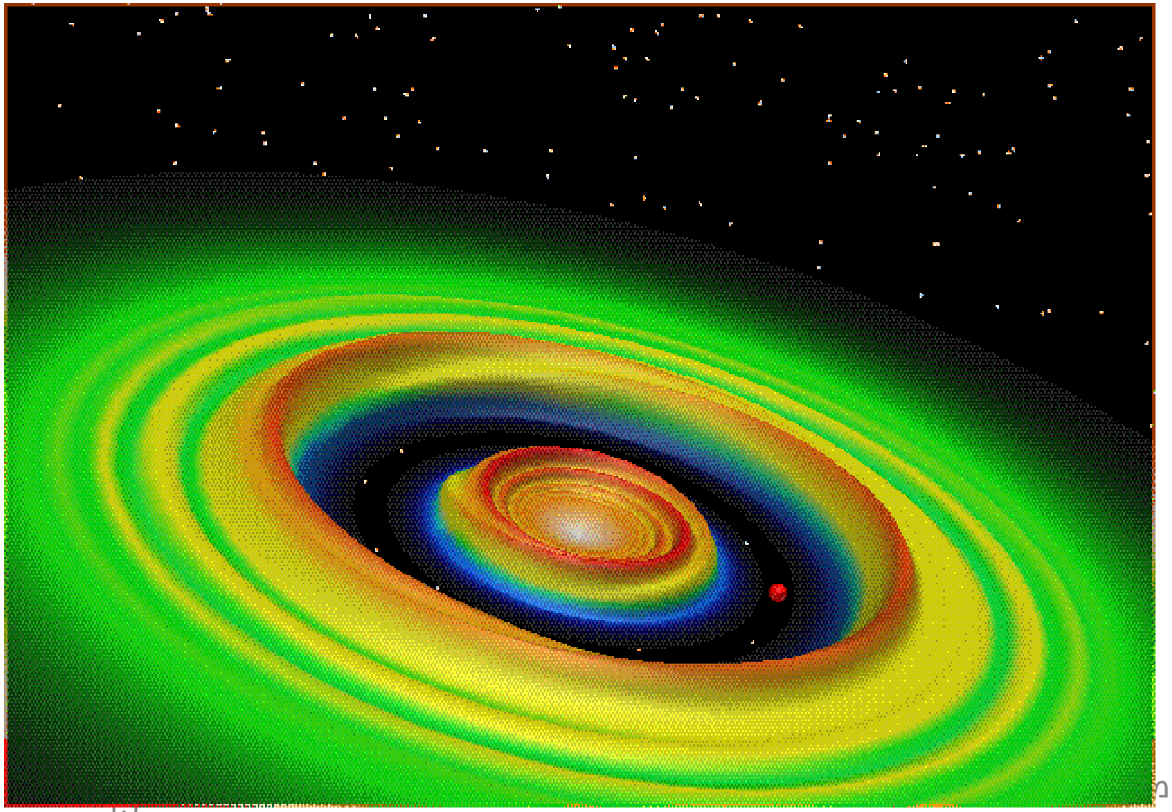
Planets discovered by RV

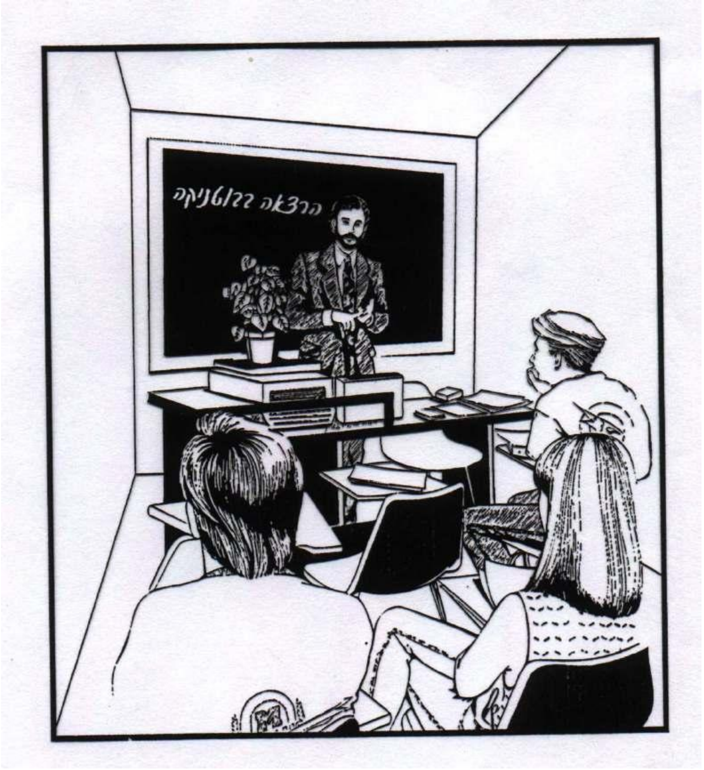
Close-in giant planets

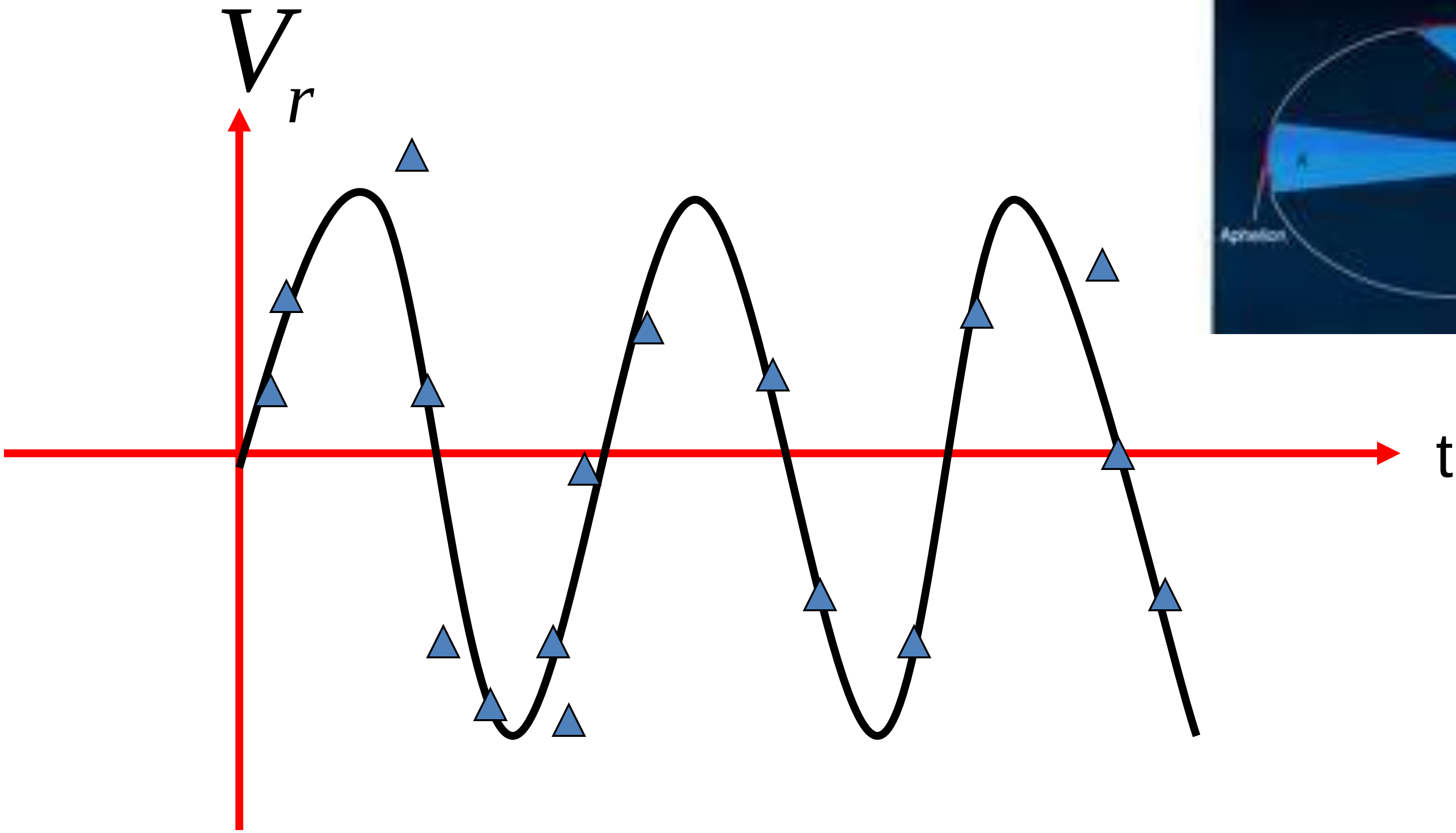
- ~~Giant planets far away~~
- Circular orbits
- Orbits aligned with Solar spin

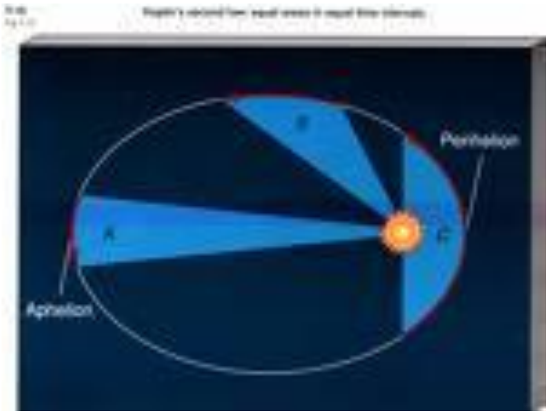


נדידה






V_r
t


Perihelion
Aphelion

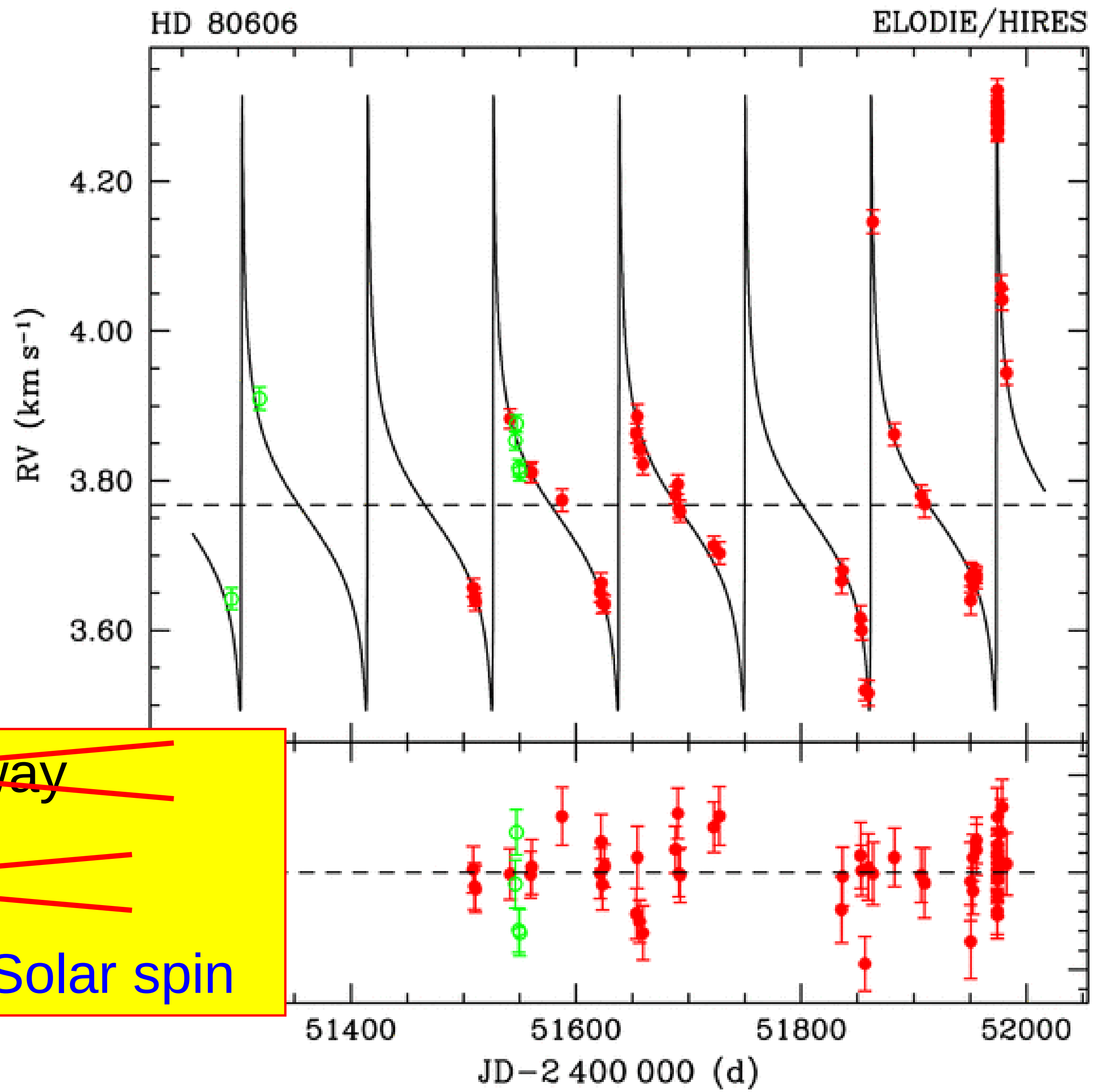
HD80606

(Naef et al. 2001)

e=0.93

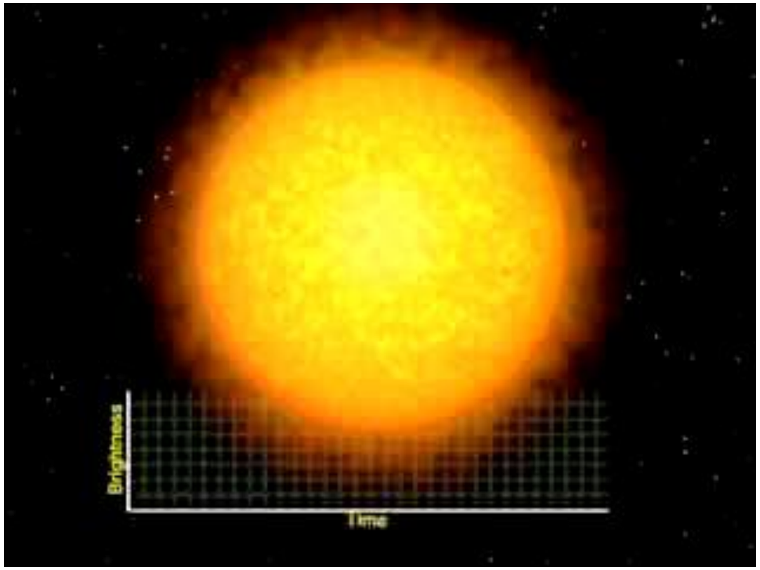
P=112 days

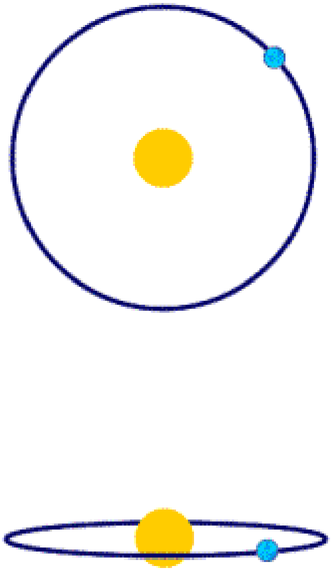
msini=$4M_{Jup}$



- ~~Giant planets far away~~
- ~~Circular orbits~~
- Orbits aligned with Solar spin

Transits

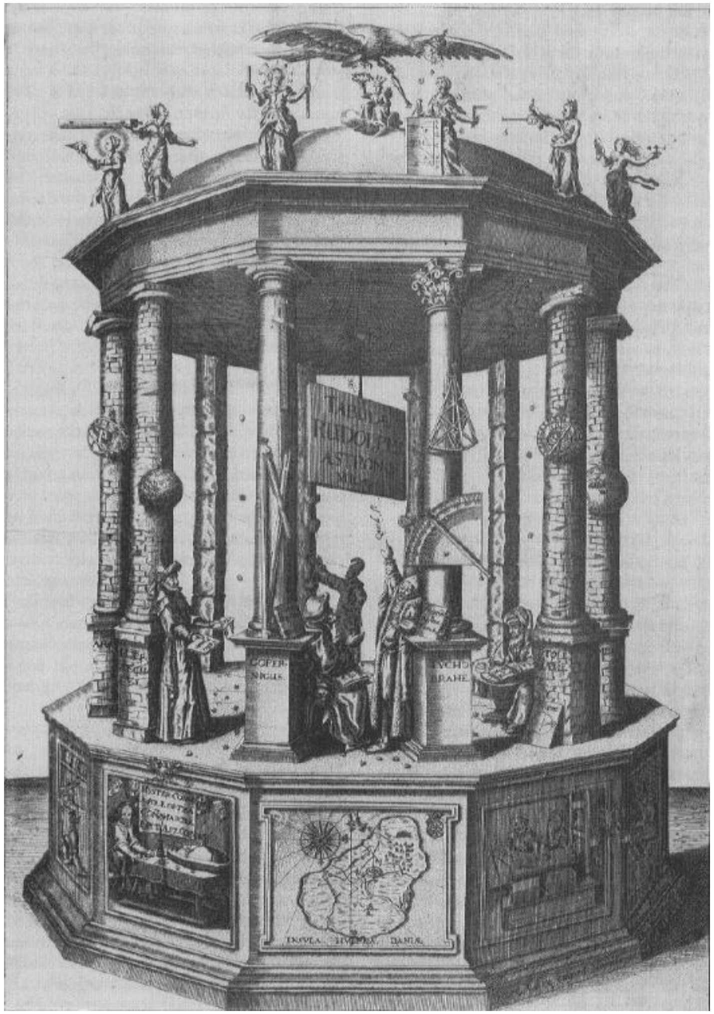




$$P_{transit} = \frac{R_* + R_p}{a}$$

The inclination *(i)* must be very close to 90°

יוהאן קפלר (1571-1630)



הלוחות הרודולפיניים 1627

November 7, 1631

Pierre Gassendi צפה במעבר של כוכב חמה

בדיוק לפי החישובים של קפלר

ניבוי של מעבר transit של כוכב חמה על פני השמש

7 בנובמבר 1631 +/- יום או יומיים

Next Step - A Transiting Planet

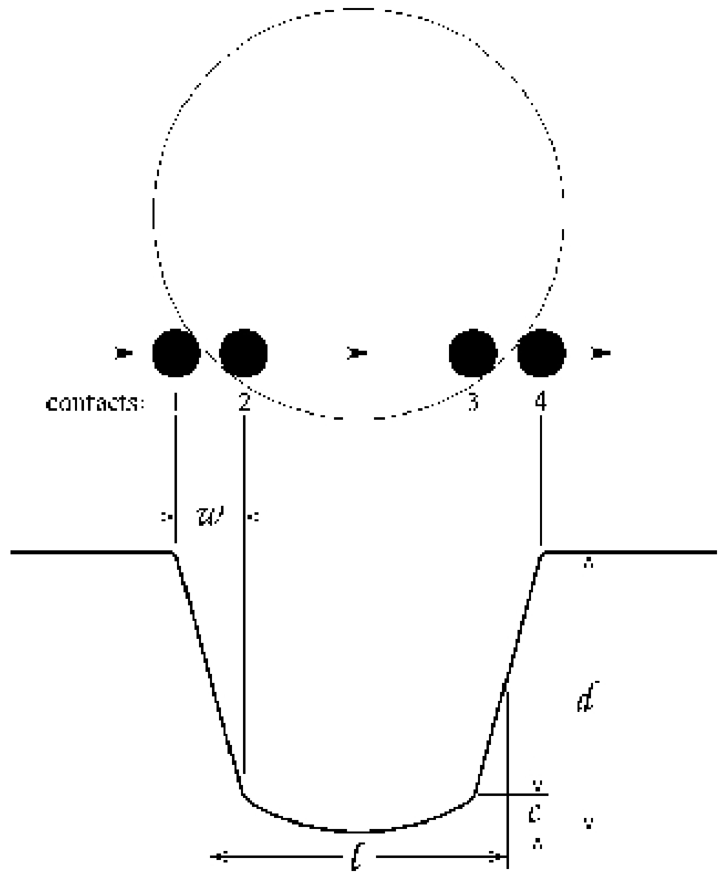
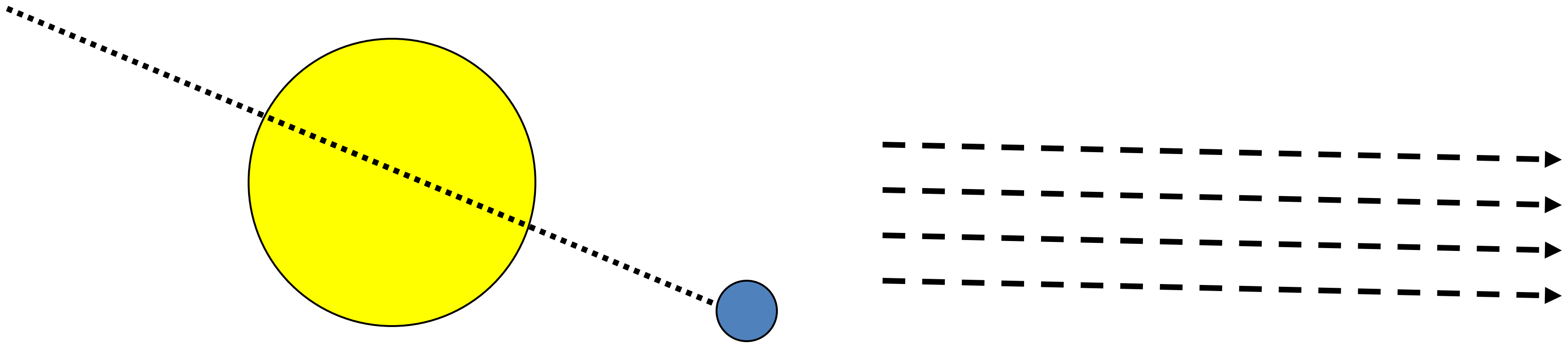
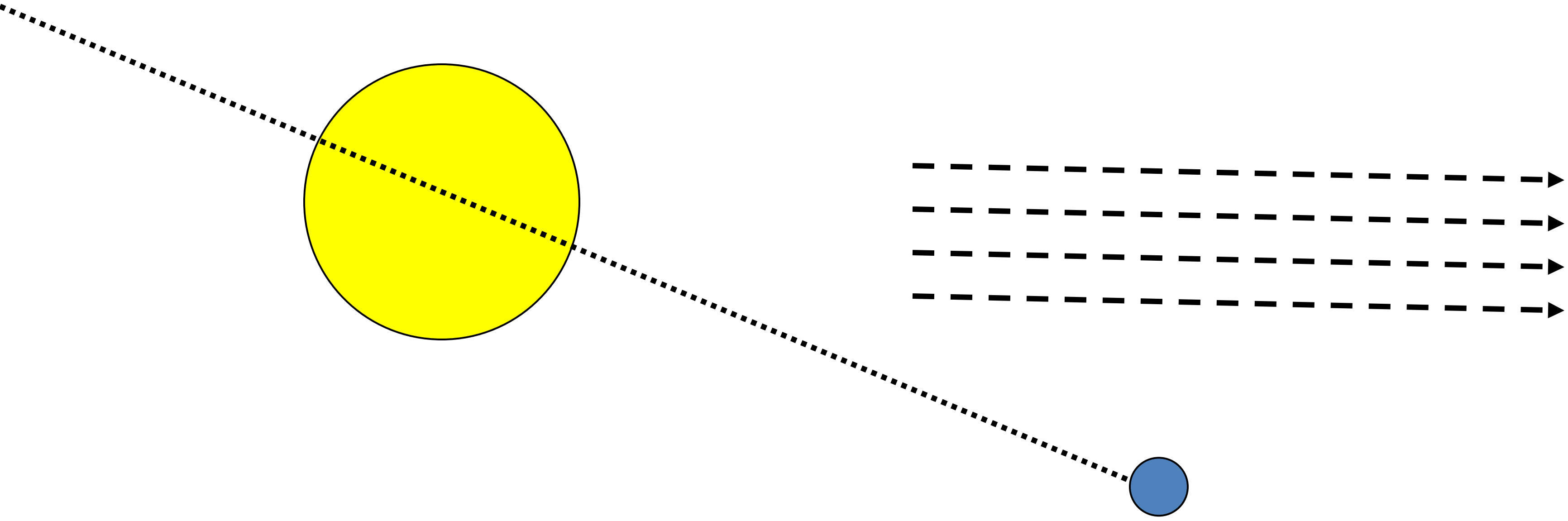


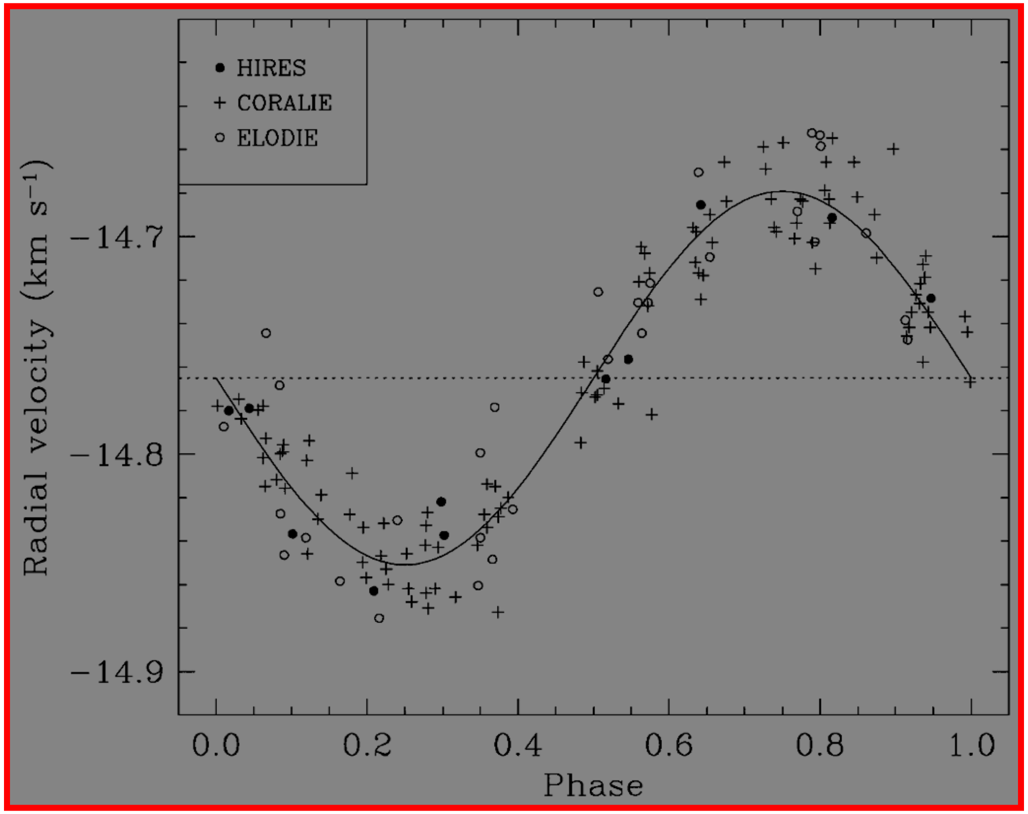
FIG. 4.—Schematic illustration of the light curve of a transiting planet. Measurable quantities are the duration of the transit *l*, the transit depth *d*, the ingress/egress duration *w*, and the central curvature of the light curve *C*. Given the orbital speed (which follows from the orbital period and the stellar mass), these quantities determine the radii of the star and of the planet, the orbital inclination, and the degree of limb darkening.





HD 209458

Mazeh *et al.*, 2000



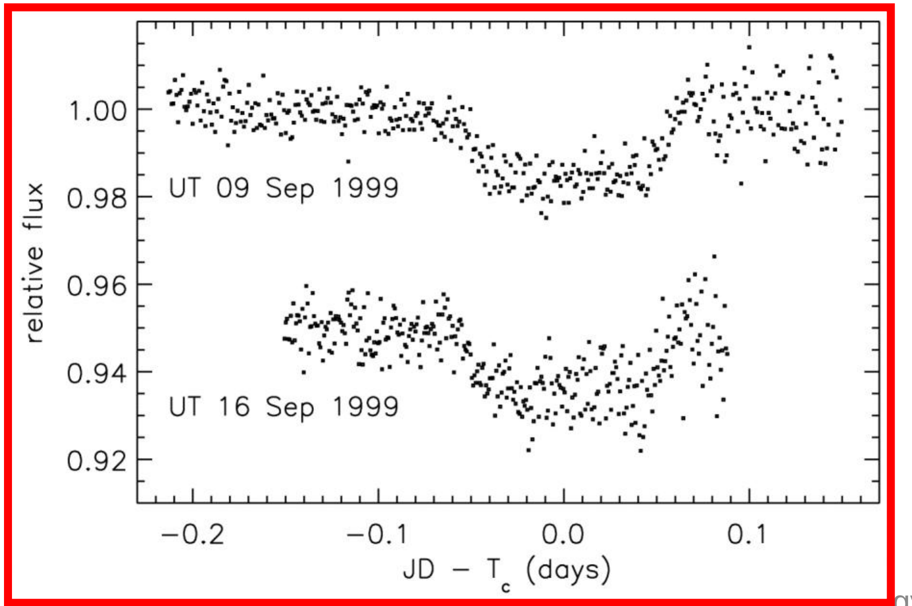
$$M_{\mathtt{Planet}} Sin(i) = 0.68\, M_{\mathtt{Jup}}$$

$$P_{orbit} = 3.524\, days$$

HD 209458

Charbonneau, Brown, Latham & Mayor 2000

Henry, Marcy, Butler & Vogt 2000



Depth: ~1.5%

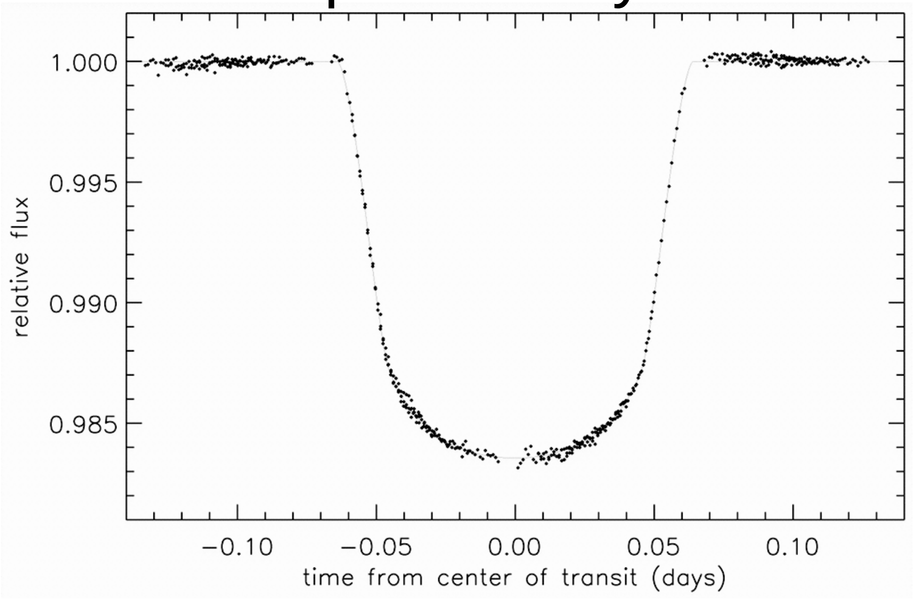
Duration: ~2.5 hours

Phase consistent with the radial velocities

HD209458

Brown, Charbonneau, Gilliland, Noyes & Burrows, 2001,

HST photometry

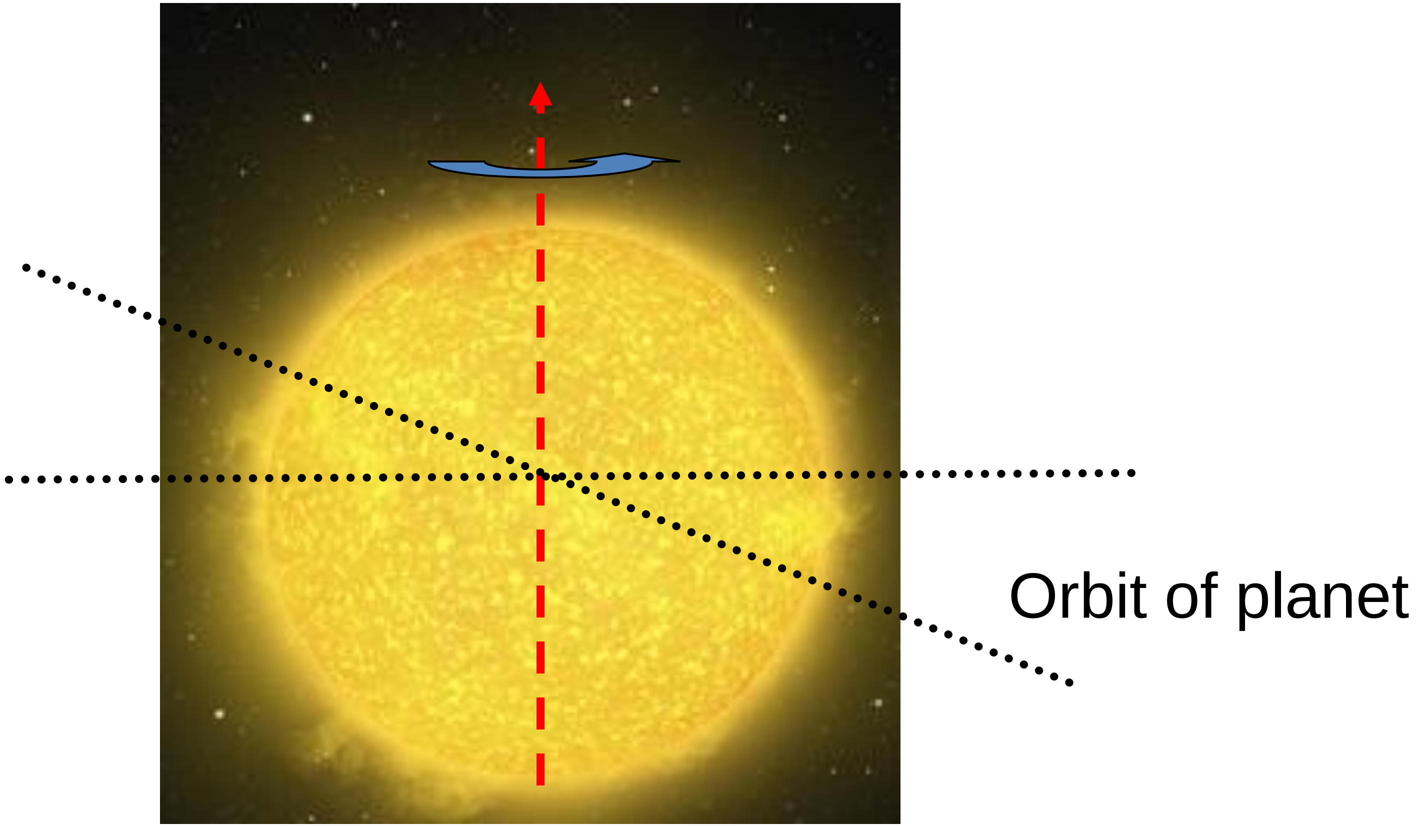


$$R_{\mathrm{Planet}} = 1.35 \pm 0.06\ R_{\mathrm{Jup}}$$

$$i = 86^{\circ}.7 \pm 0^{\circ}.1$$

$$\overline{\rho} = 0.35\ \mathrm{g\ cm^{-3}}$$

Spin-orbit relative inclination



Stellar Spin-Planetary orbit relative inclination

The Rossiter-McLaughlin effect

Gaudi & Winn 2007:

$$\Delta V_* \approx \left(\frac{r_{planet}}{R_*} \right)^2 V_{*,rotation}$$

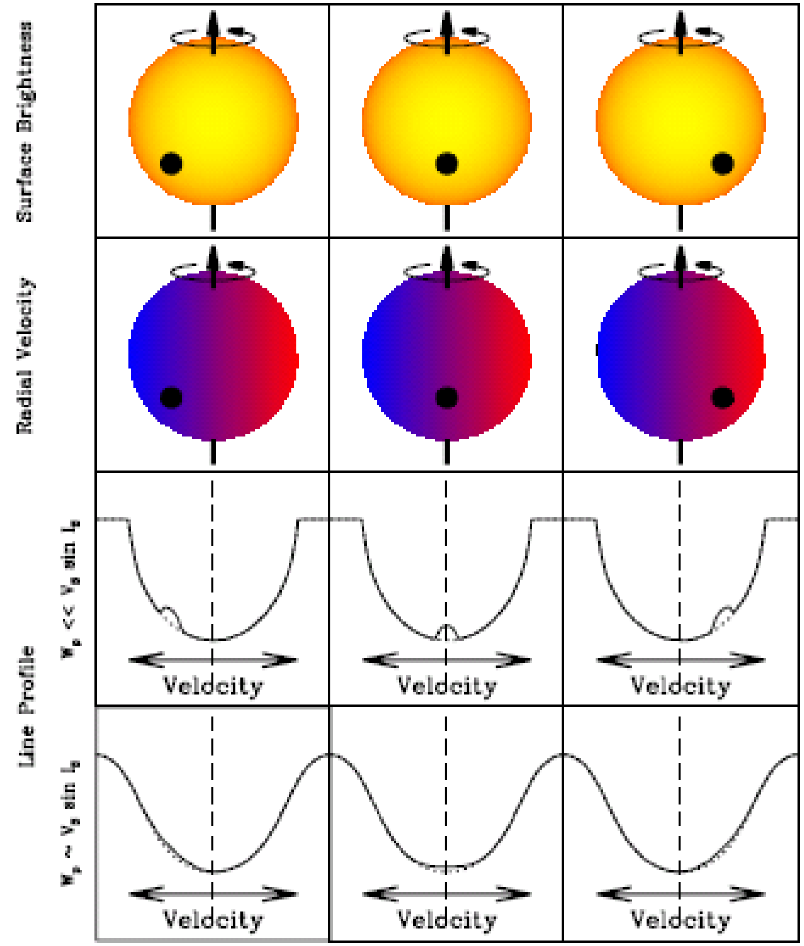


FIG. 1.— The physics of the RM effect. Top row. Three successive phases of an exoplanetary transit. Second row. Same, but the projected stellar rotation speed at each point has been color coded, neglecting differential rotation. At each phase, the planet hides a different velocity component. Third row. Illustration of an observed stellar absorption line, for the case of purely rotational broadening, i.e., the net broadening due to all other mechanisms is much less than the rotational broadening ($W_p \ll V_S \sin I_S$). The missing velocity component is manifested as a time-variable bump in the line profile. Fourth row. Same, but for the case $W_p \sim V_S \sin I_S$, in which other line-broadening mechanisms besides rotation are important.

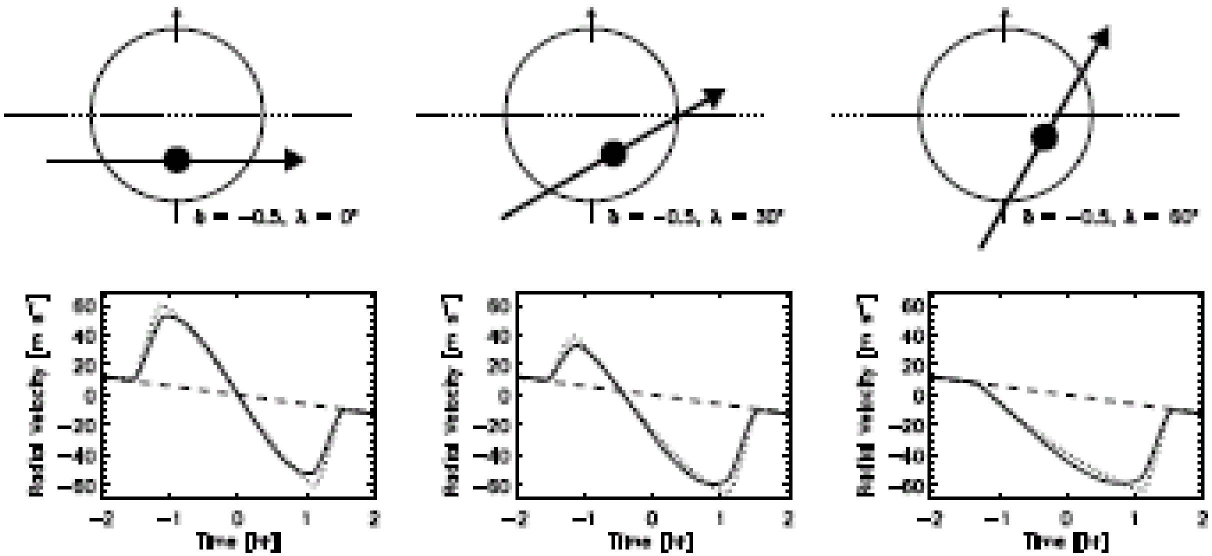
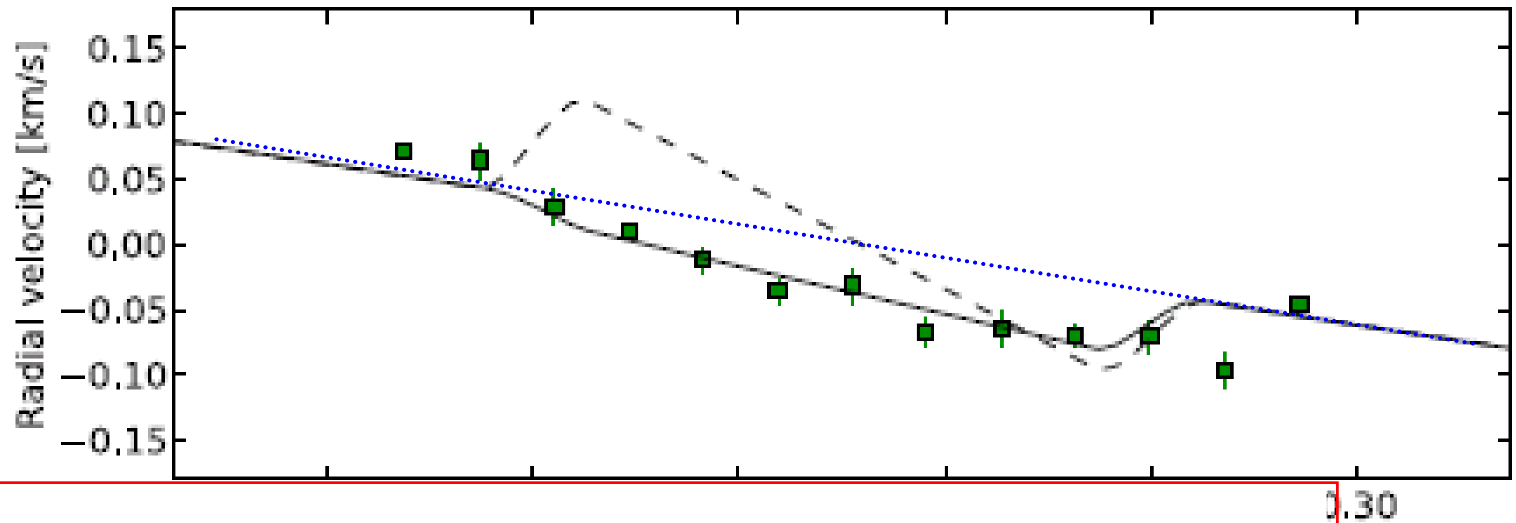


FIG. 2.— The dependence of the RM waveform on λ. Three different possible trajectories of a transiting planet are shown, along with the corresponding RM waveform (as computed with the formulae of Ohta et al. 2005). The trajectories all have the same impact parameter and produce the same light curve, but they differ in λ and produce different RM curves. The dotted lines are for the case of no limb darkening ($\epsilon = 0$), and the solid lines are for $\epsilon = 0.6$.

CoRoT-1b

The R-M effect



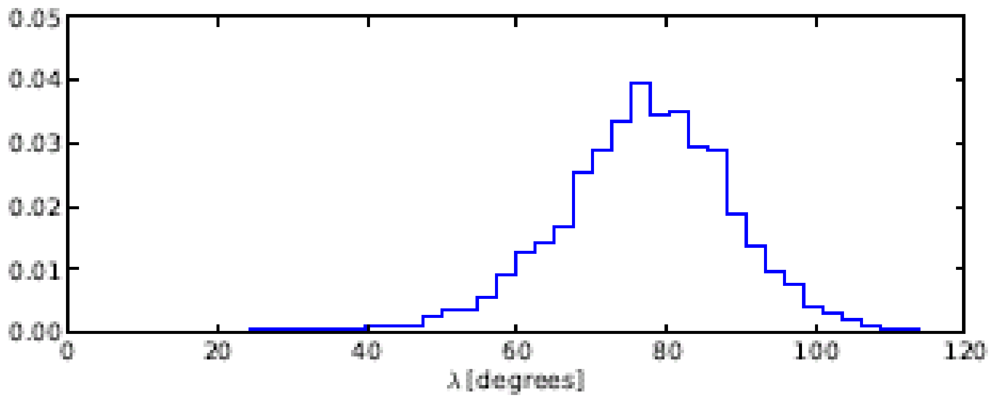


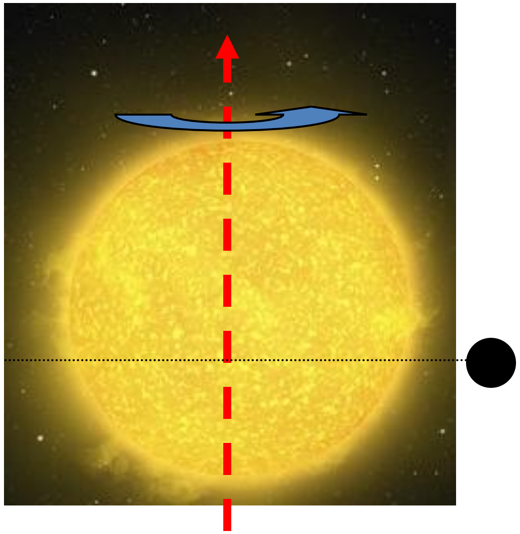
Figure 3. Probability distribution of the projected spin-orbit angle according to the MCMC integration.

solid line
vith $\lambda = 0$

Winn et al. 2009

HAT-P-7:

$$\lambda = 182.5 \pm 9.4\ \mathrm{deg}$$



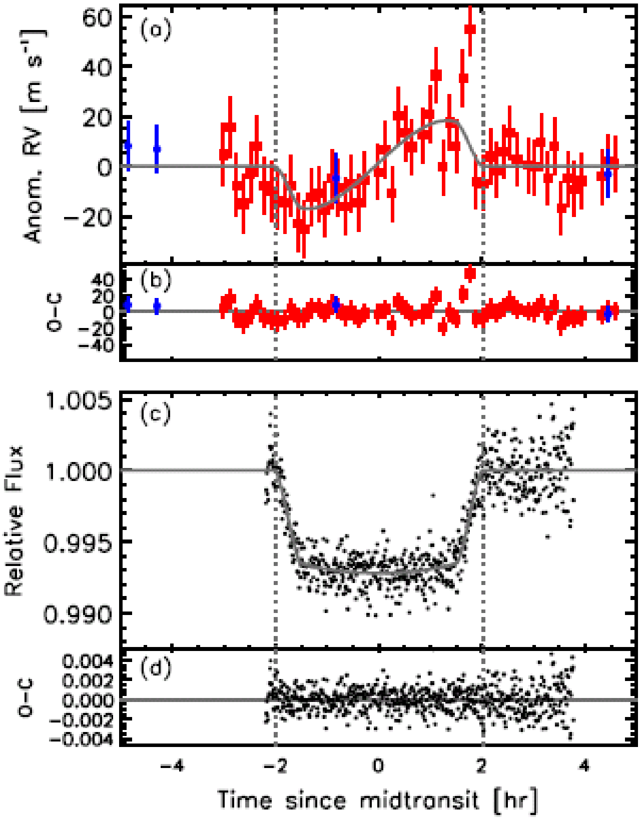


Figure 3. Spectroscopic and photometric transit of HAT-P-7b. (a) The anomalous RV, defined as the output of the Doppler code minus the orbital RV. We observed a blueshift in the first half of the transit, and a redshift in the second half of the transit, demonstrating that the sky projections of the orbital and stellar angular momentum vectors point in opposite directions. (b) Residuals. Red squares are HDS data from 2009 July 1, and blue circles are HIRES data obtained on various nights in 2007 and 2009. (c) The relative flux, observed in the Sloan *i* band with the FLWO 1.2 m telescope and Keplercam. (d) Residuals. In panels (a) and (b), the gray line shows the best-fitting model.

•Giant planets far away

•Circular orbits

•Orbits aligned with Solar spin

e=0

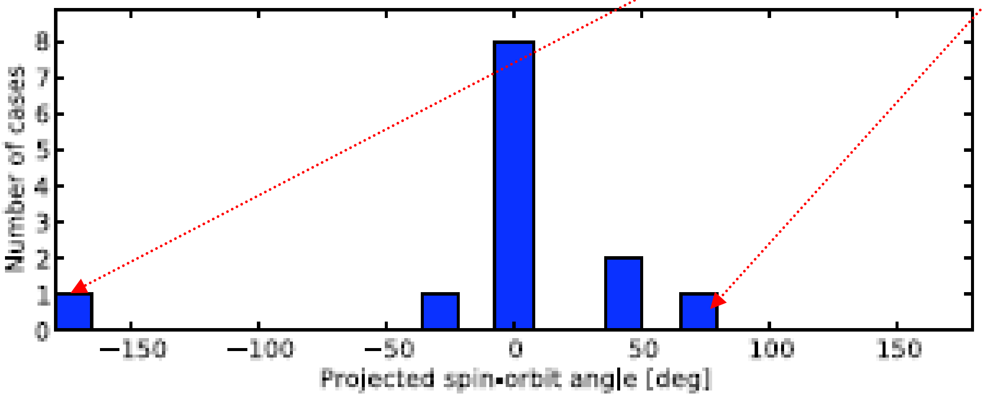
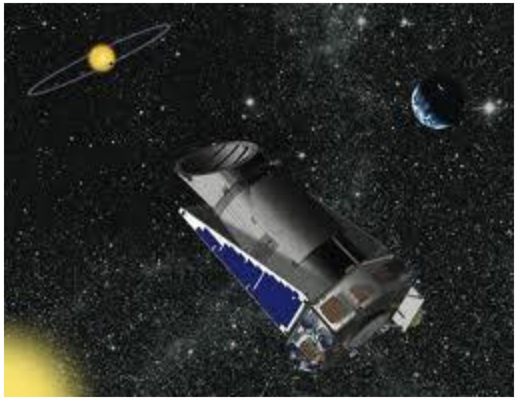


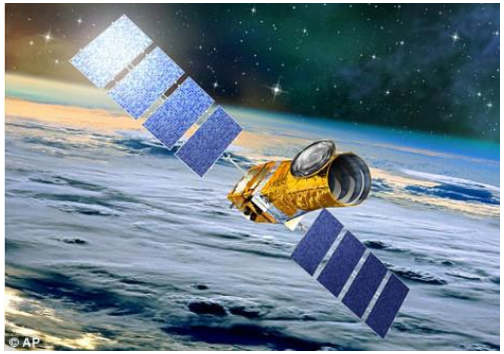
Figure 4. Distribution of projected spin-orbit angles for systems in Table 3.

תצפיות מהחלל

Kepler

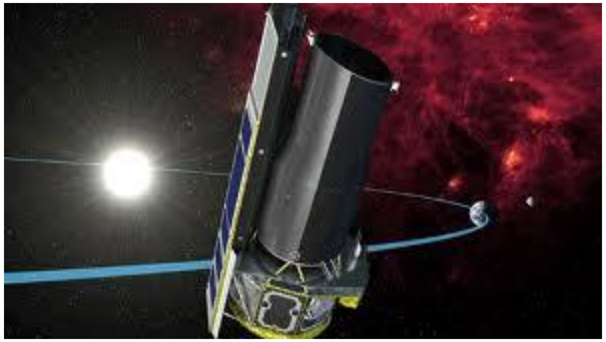


CoRoT

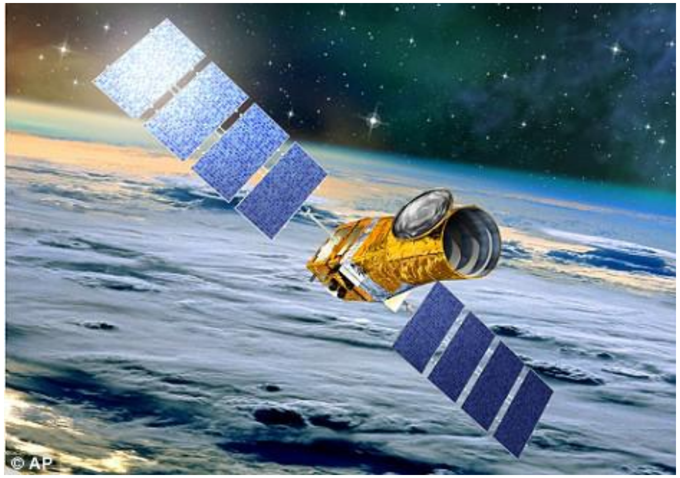


HST

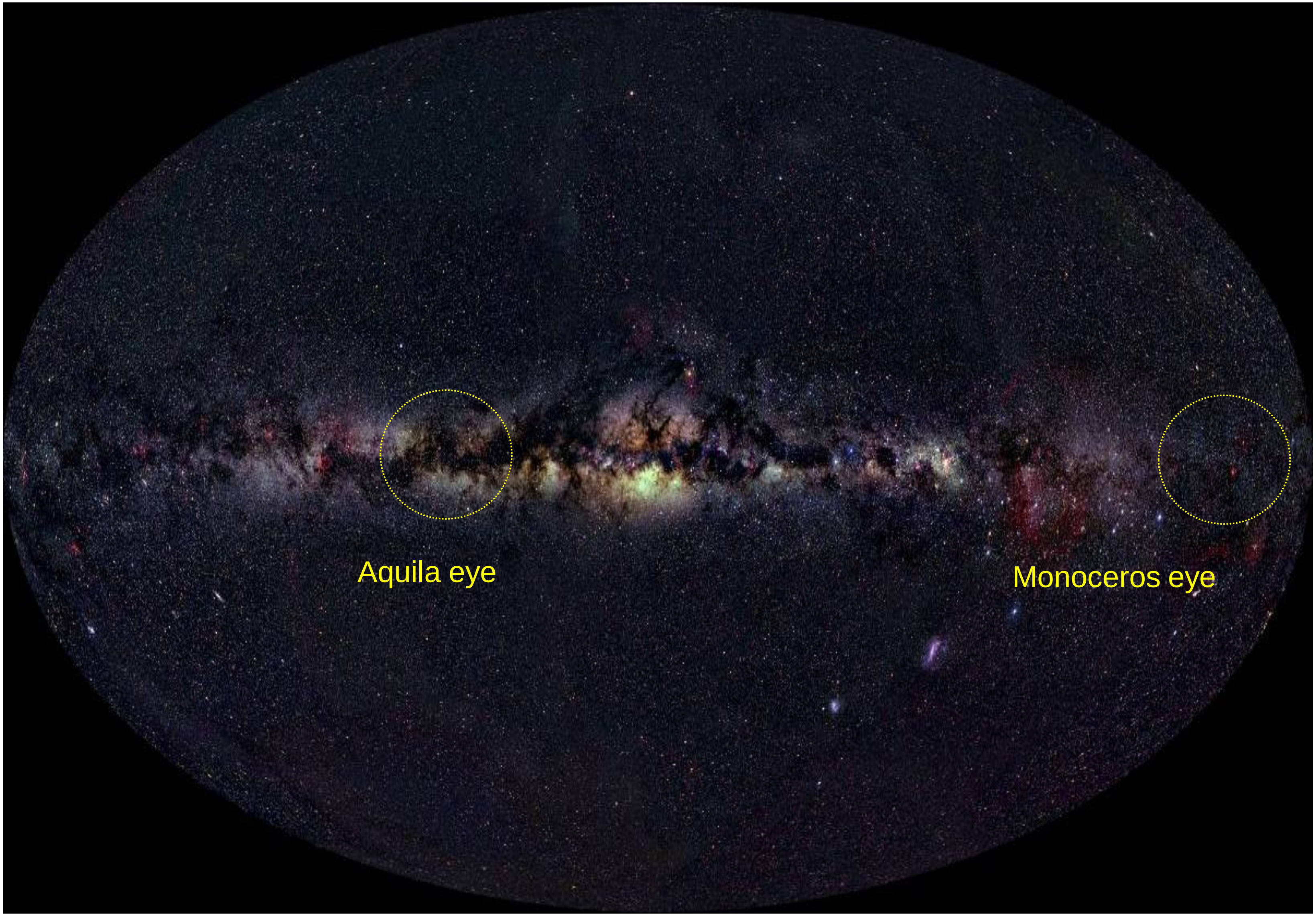
Spitzer

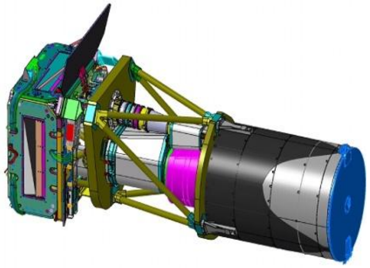


The CoRoT mission



- A French CNES mission with European partners & Brazil
- 27cm telescope with polar orbit
- Launched on 12 / 27 / 2006


Aquila eye
Monoceros eye

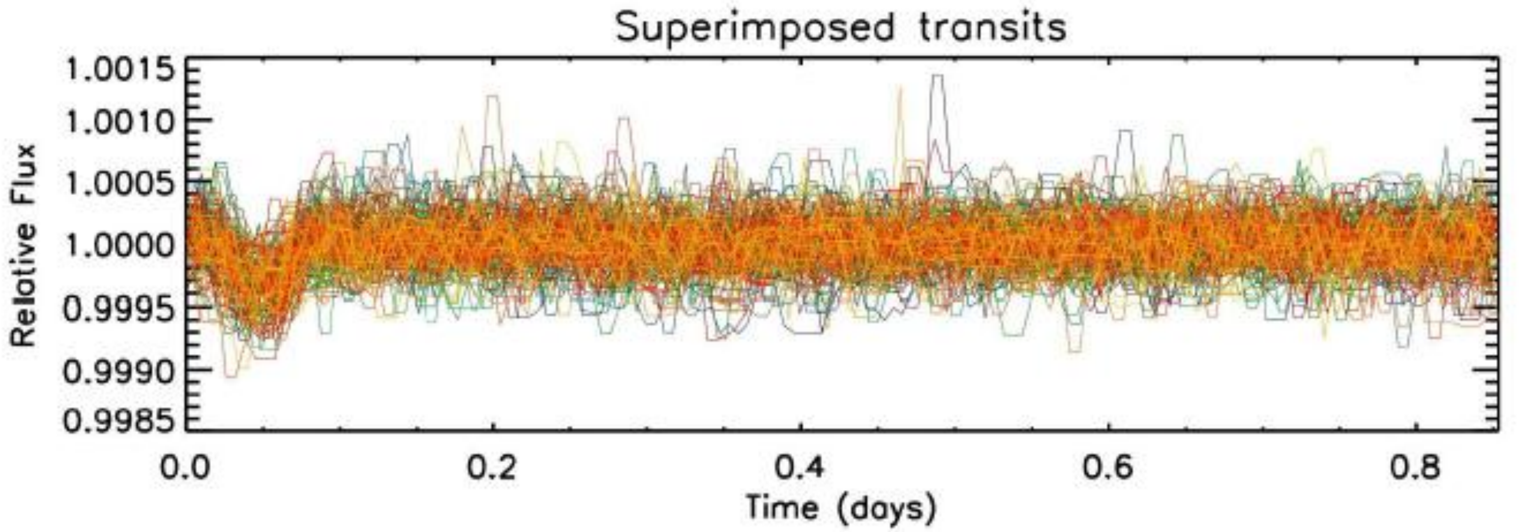


The CoRoT Satellite

- A French CNES mission with European partners & Brazil
  [+ S. Aigrain, T. Mazeh, A. Shporer]
- 27cm telescope with polar orbit
- Joint stellar seismology & exoplanets transits mission
- Launched on 12 / 27 / 2006

- 5 fields of 4 square degrees observed, including two for ~150 days at ~mid-term of the mission.
- ~30,000 dwarf stars observed between 11 < Vmag < 16
- Photometric data is gathered in a « mask » of pixels

CoRoT-7b

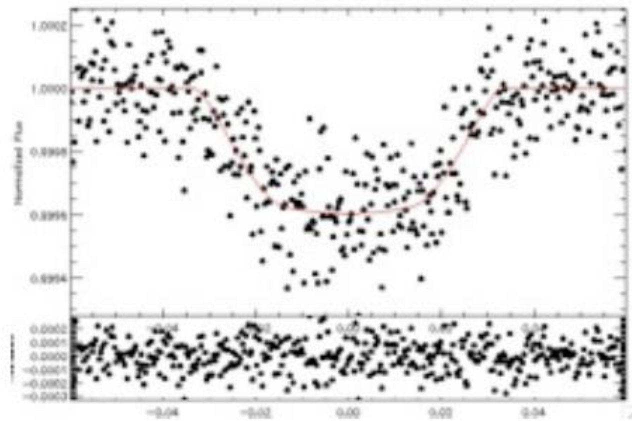


P=20.4 hours

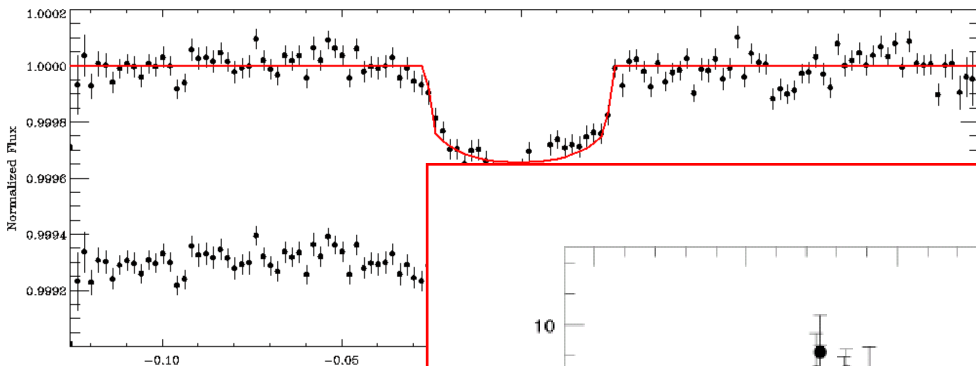
CoRoT-7b: first super –earth transiting planet

- First detected by alarm mode
- 153 transits,

all ~ seen when superimposed



i = 59.6, u+=0.6, u-=0.2



d=150pc

Short period : P=

>> transit depth :

compatible with R

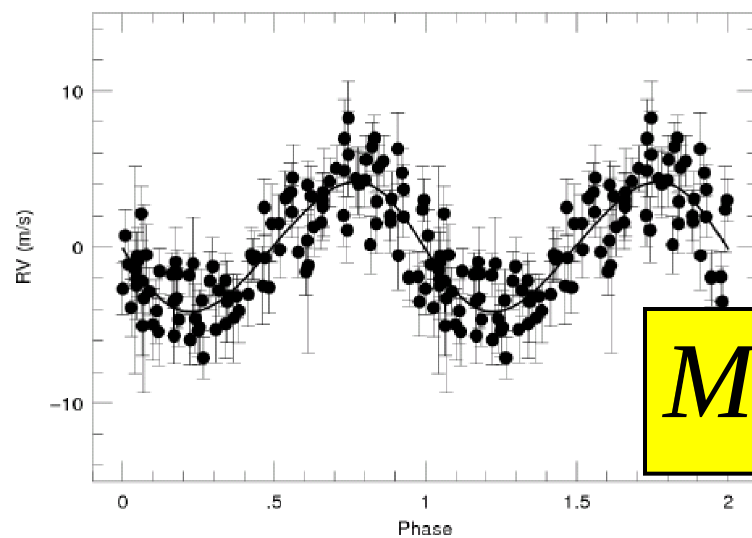
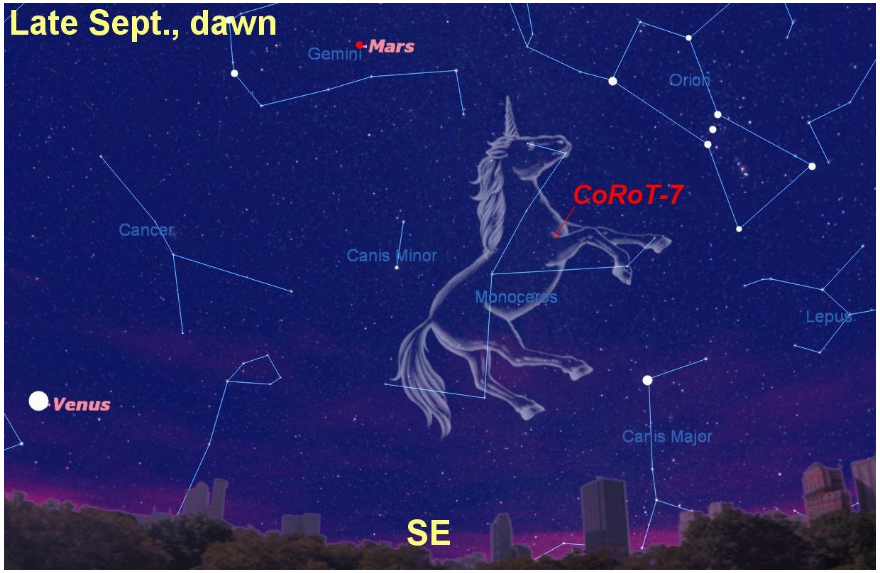
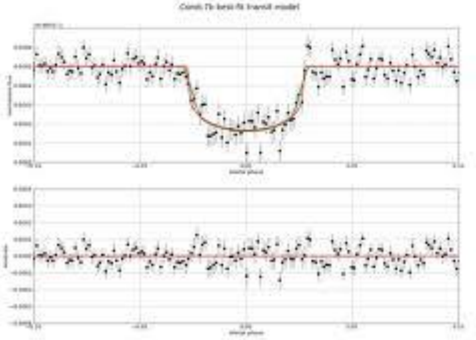


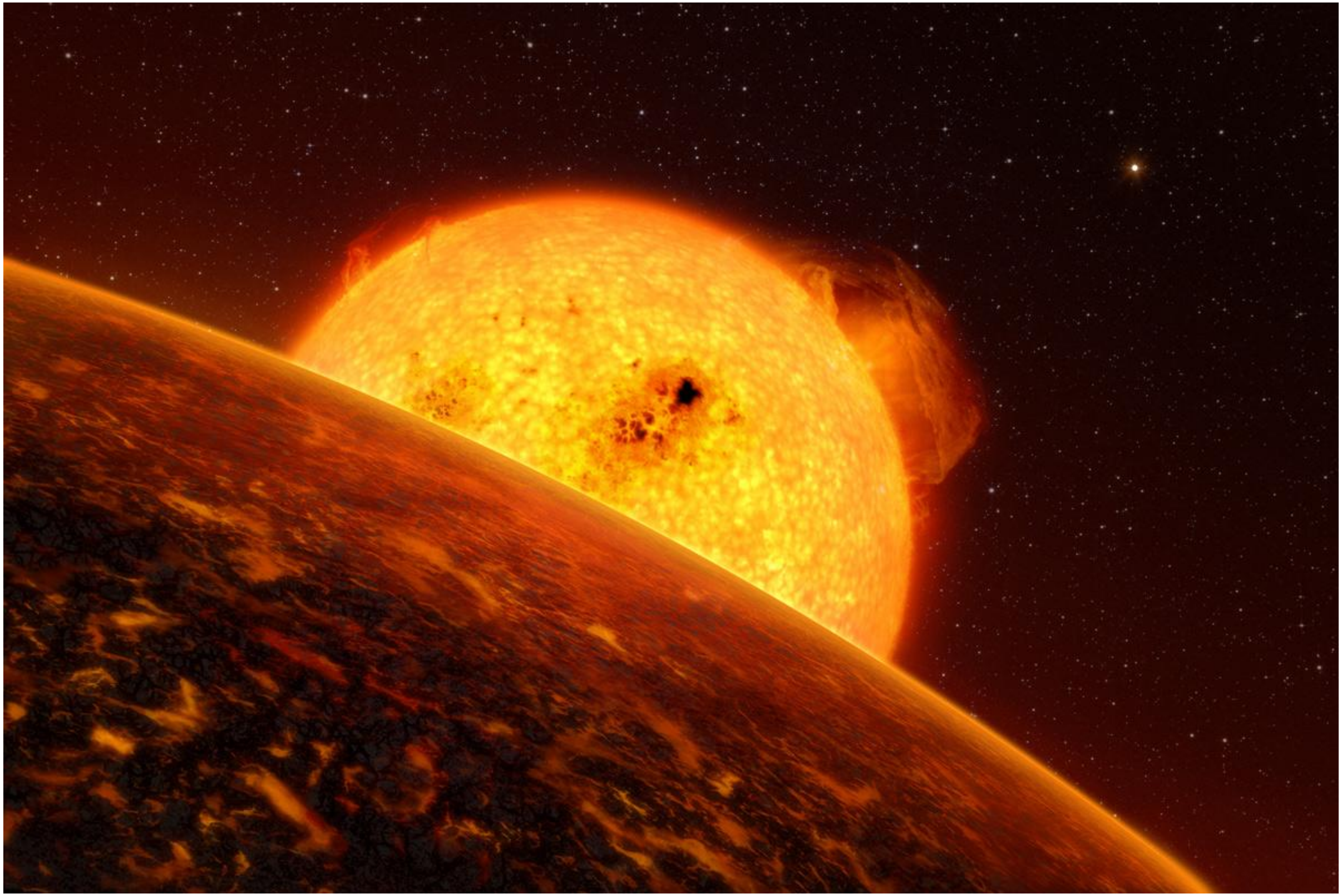
Fig. 9. Orbital solution for the 0.85-d period using the residuals from the radial velocity data after removing the contribution of all other frequencies detected by the pre-whitening procedure.

$$M \cong 5\, M_{earth}$$

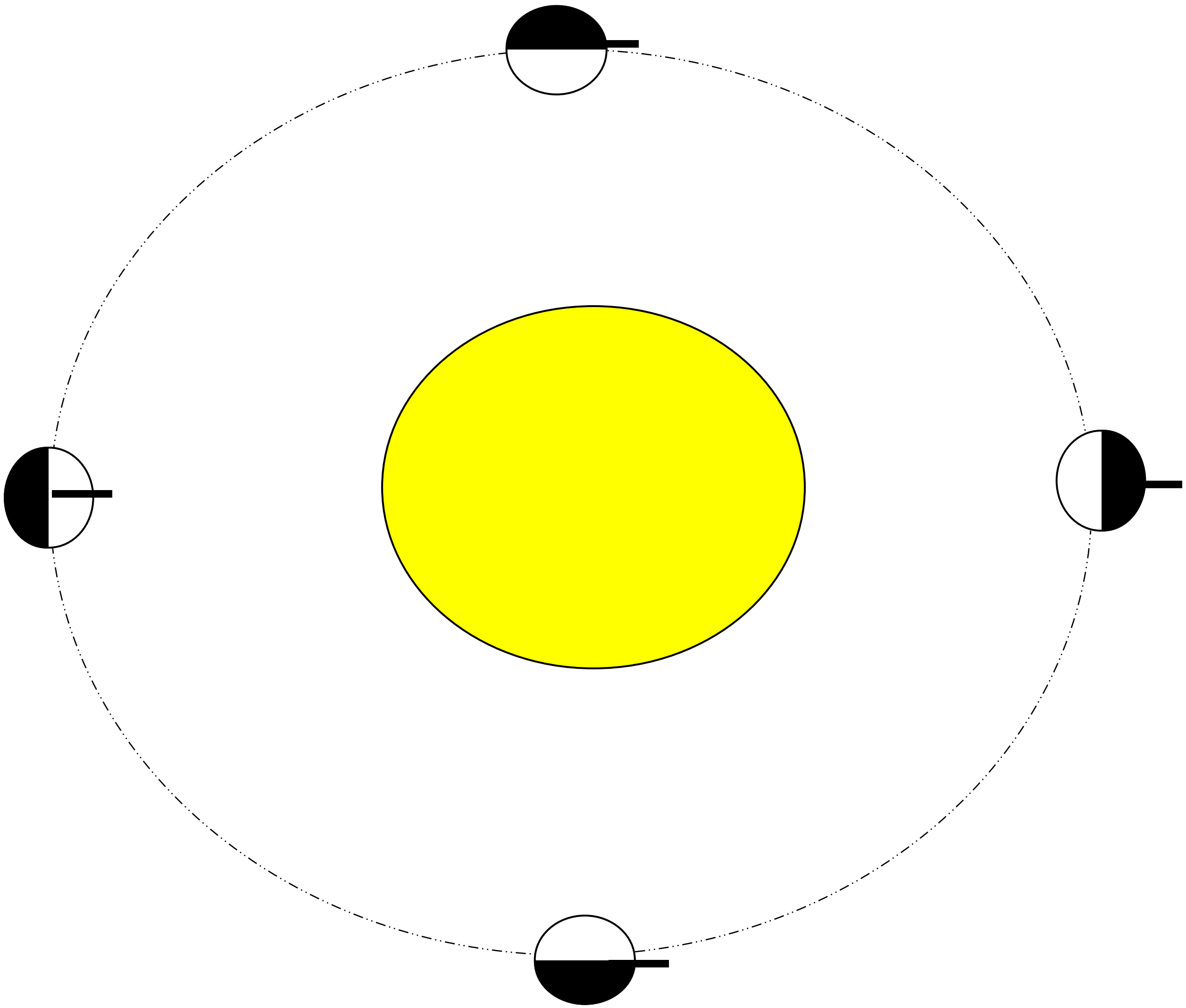

Late Sept., dawn
Gemini
Mars
Orion
CoRoT-7
Cancer
Canis Minor
Monoceros
Lepus
Venus
Canis Major
SE



CoRoT-7b

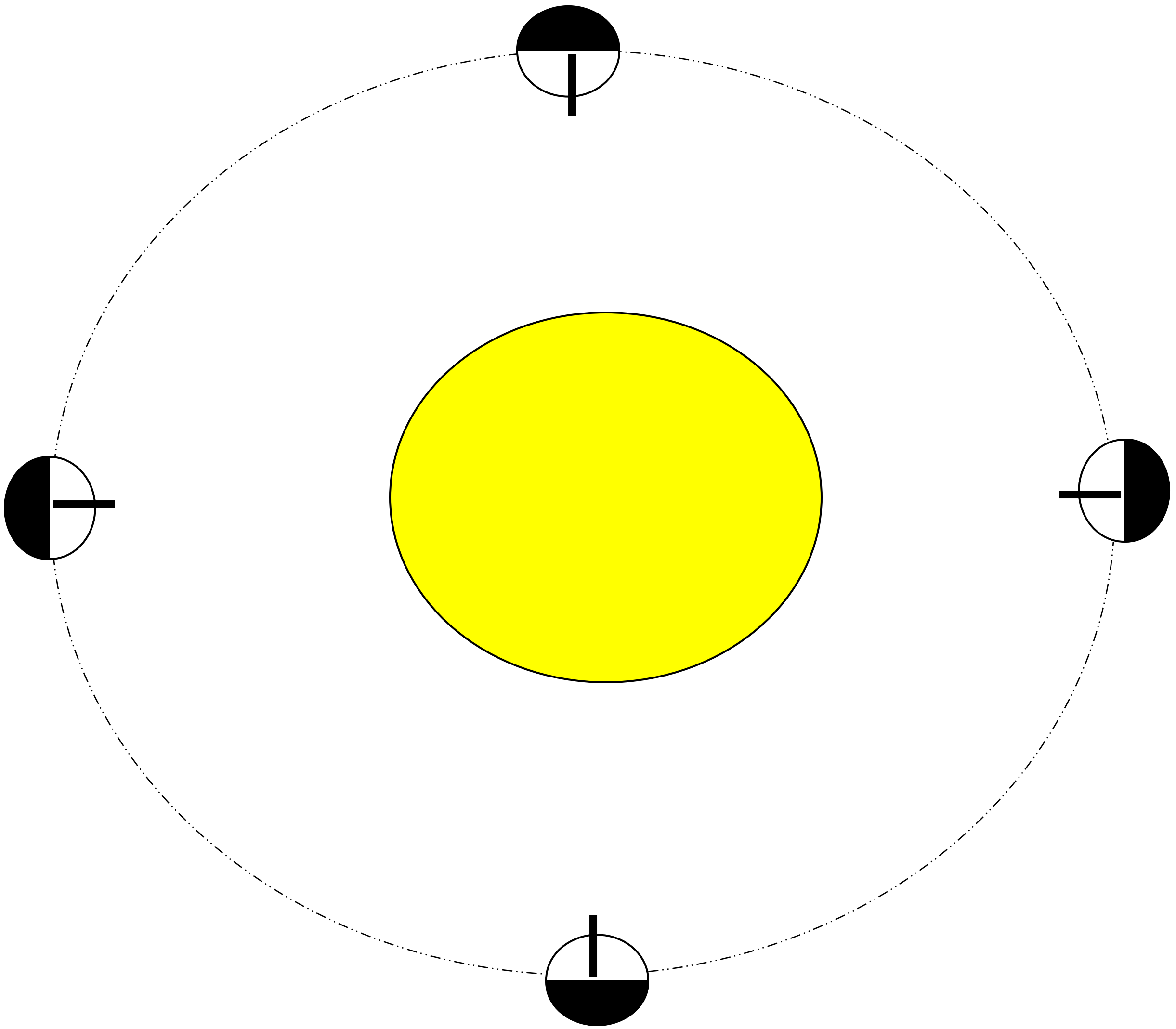


CoRoT-7b

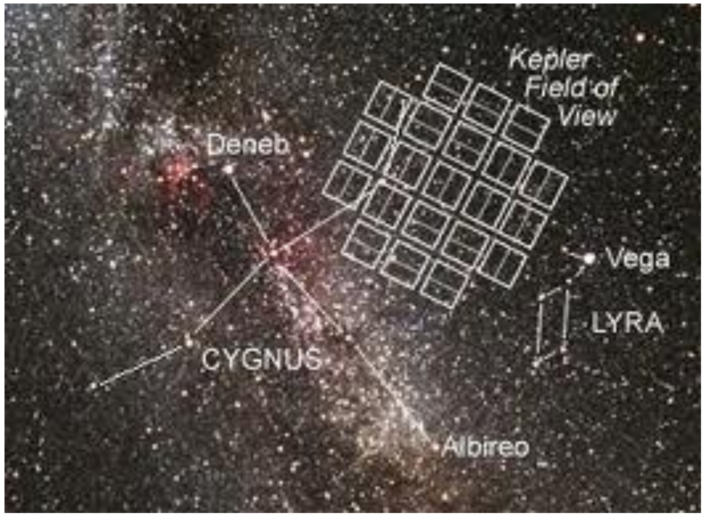


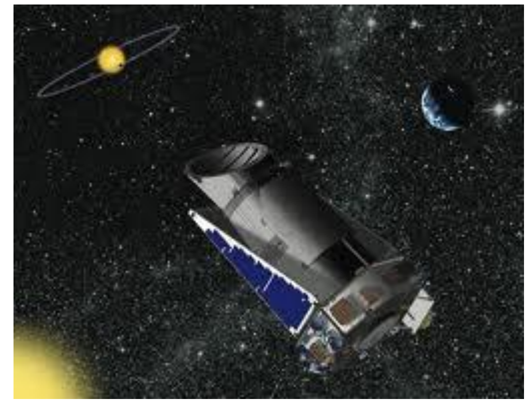
CoRoT-7b

סינכרוניזציה

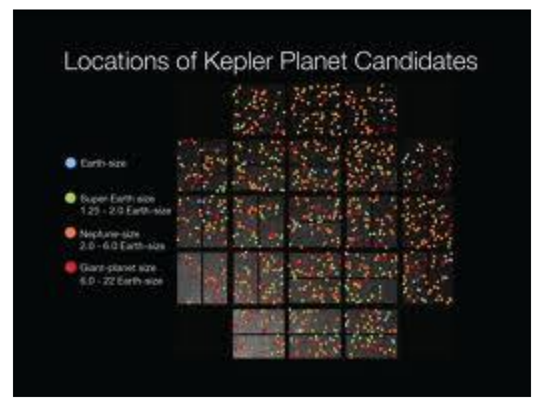


The Kepler mission

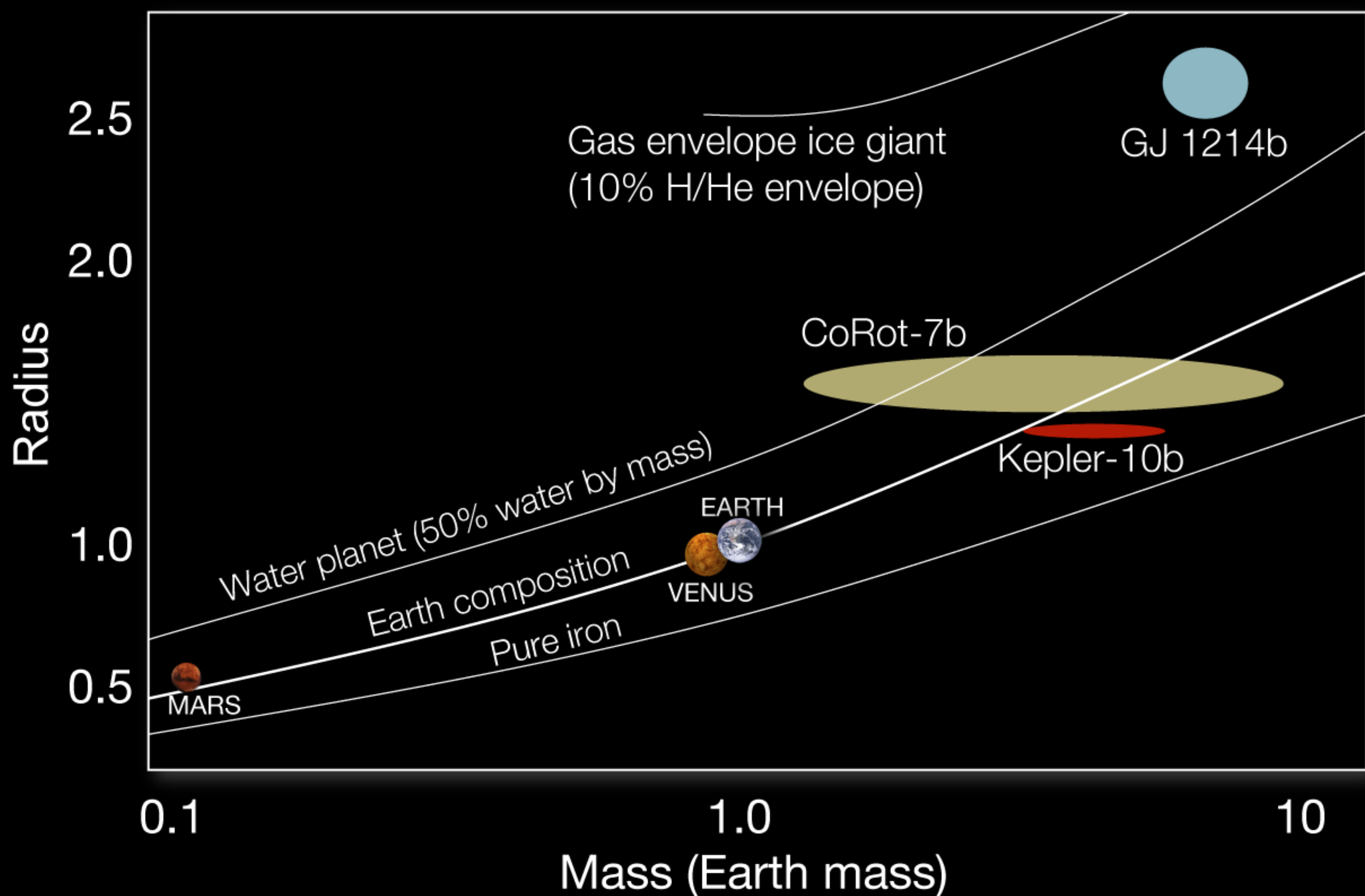


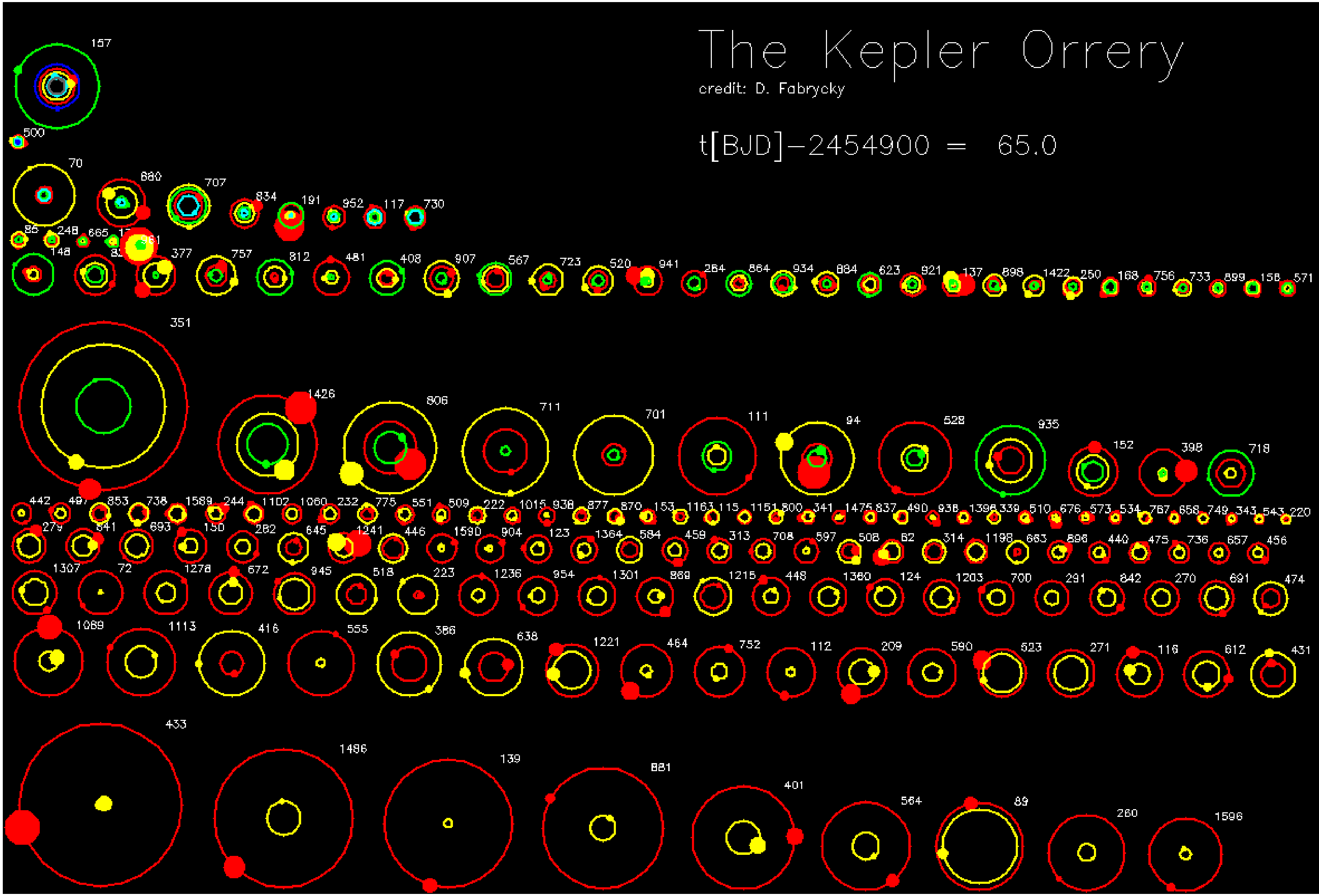


- A NASA mission
- 95 cm telescope with earth-trailing orbit
- Launched on 07 / 03 / 2009

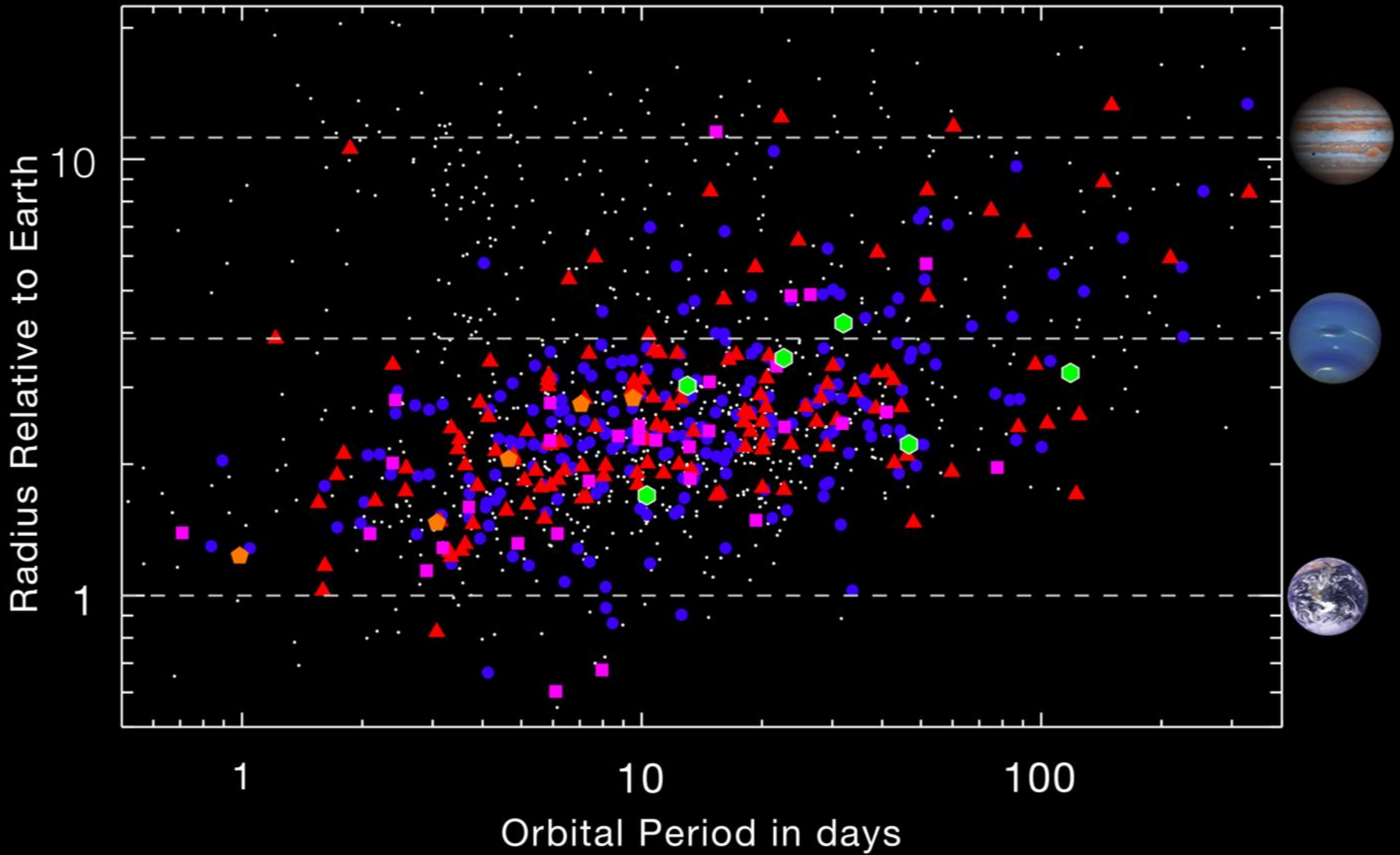


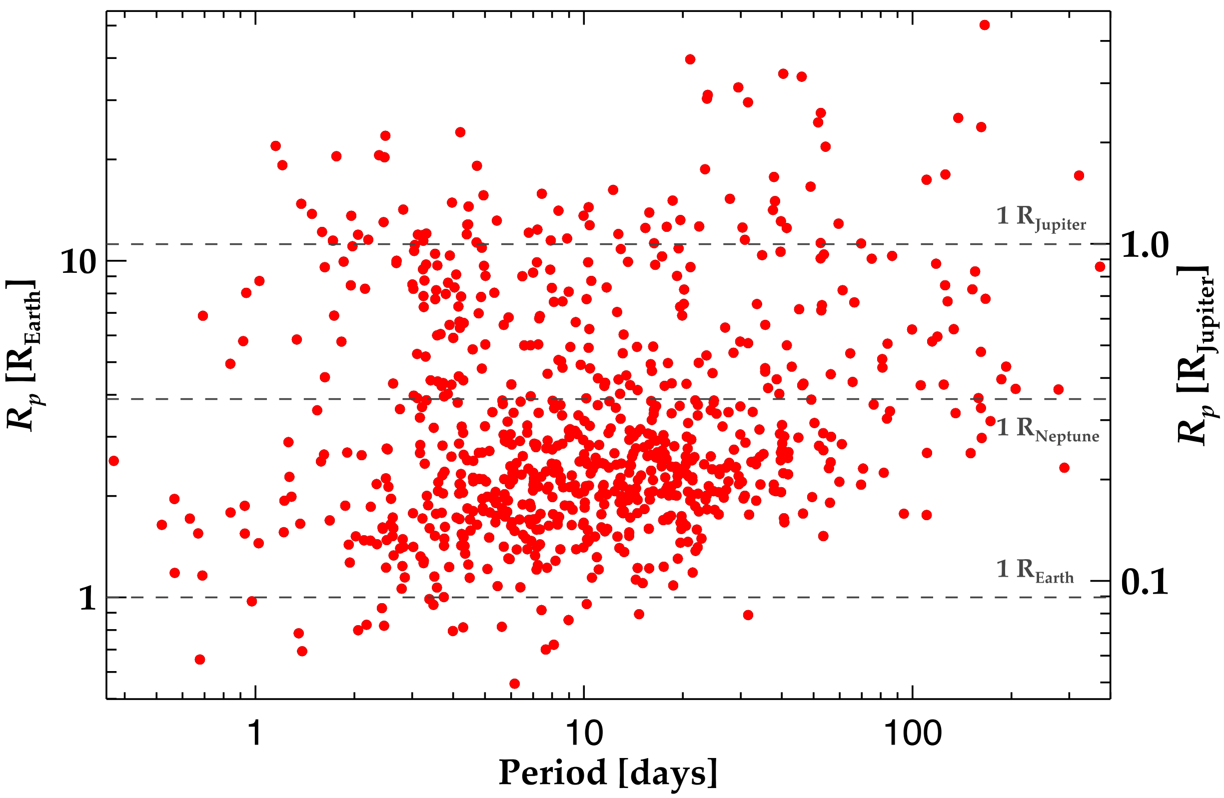
Composition of Kepler-10b




The Kepler Orrery
credit: D. Fabrycky
t[BJD]−2454900 = 65.0

Candidate Multi-Planet Systems

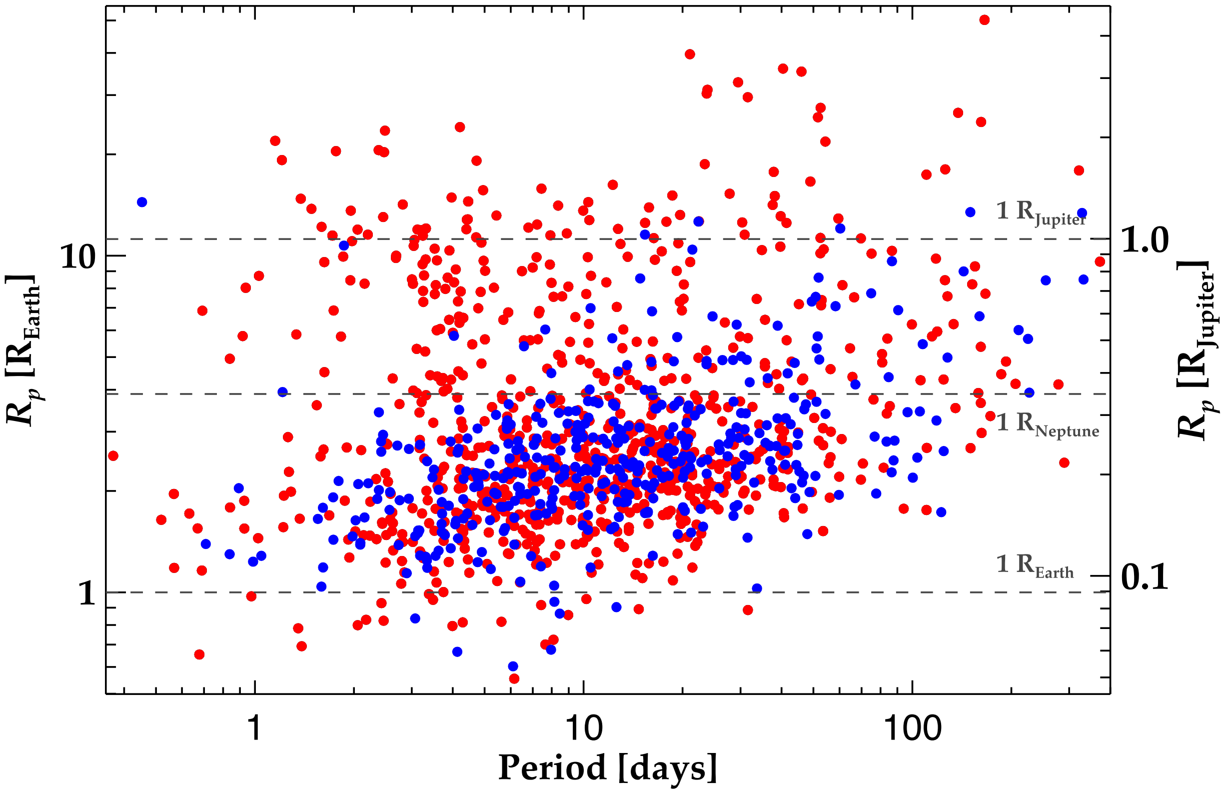




Candidates from the first 120 days of Kepler data

Planets smaller than Neptune are more common

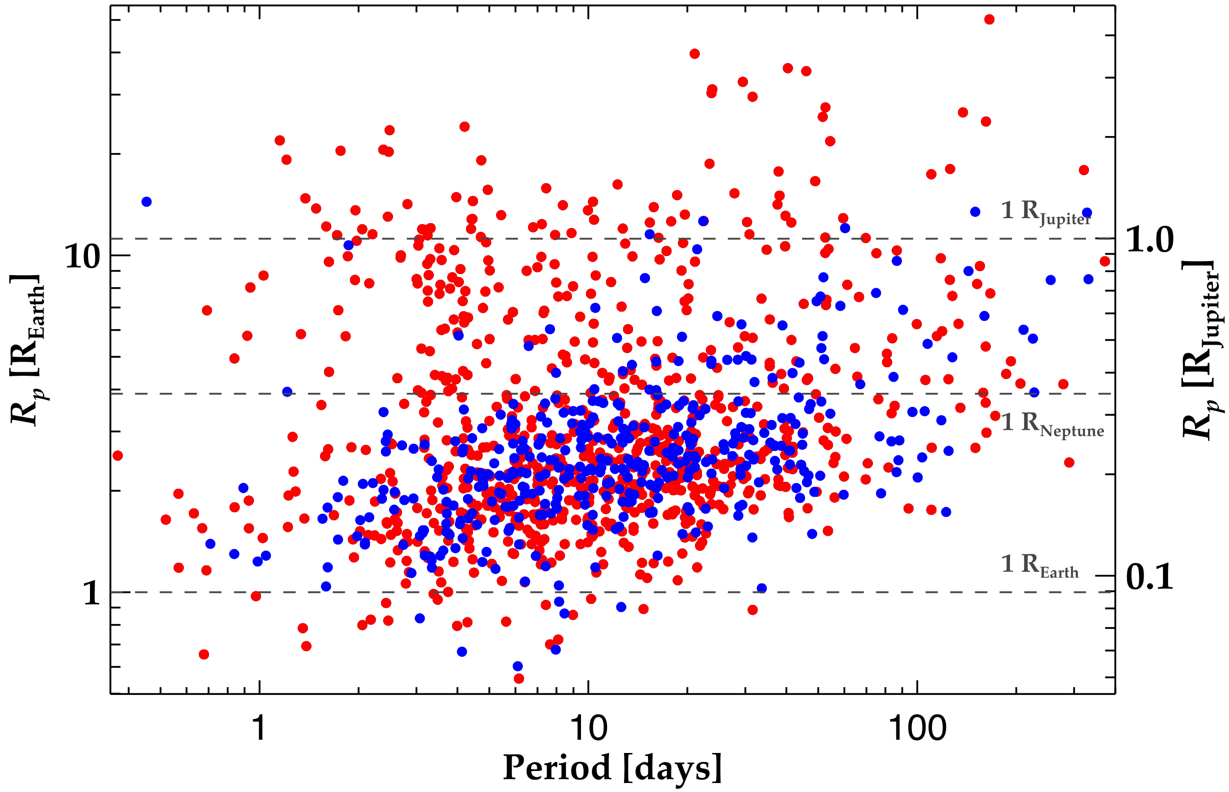
408 candidates



Hot Jupiters are rare in flat systems

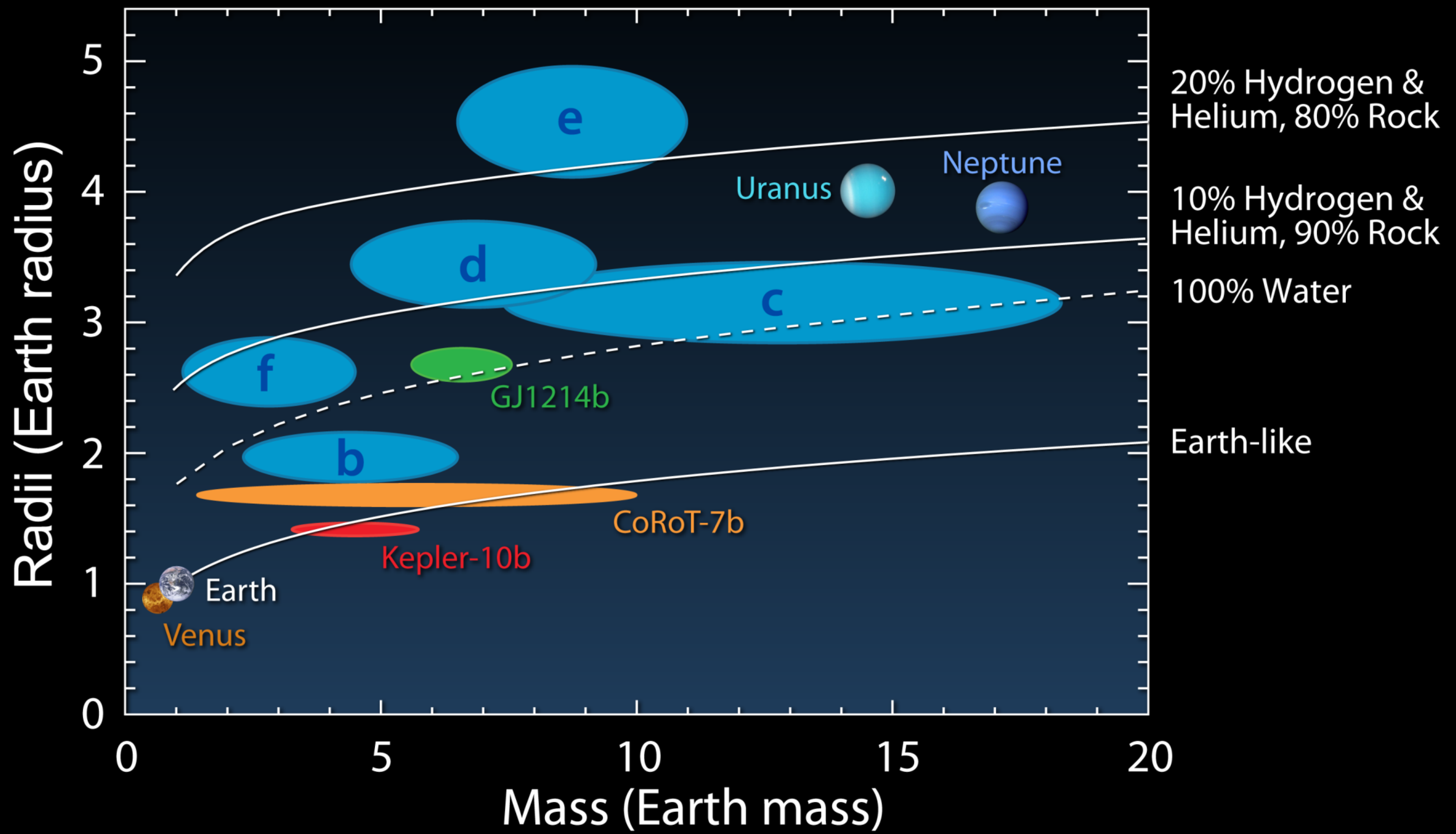
Large planets stir things up, disrupt the flatness.
Systems of small planets have more sedate histories

408 candidates

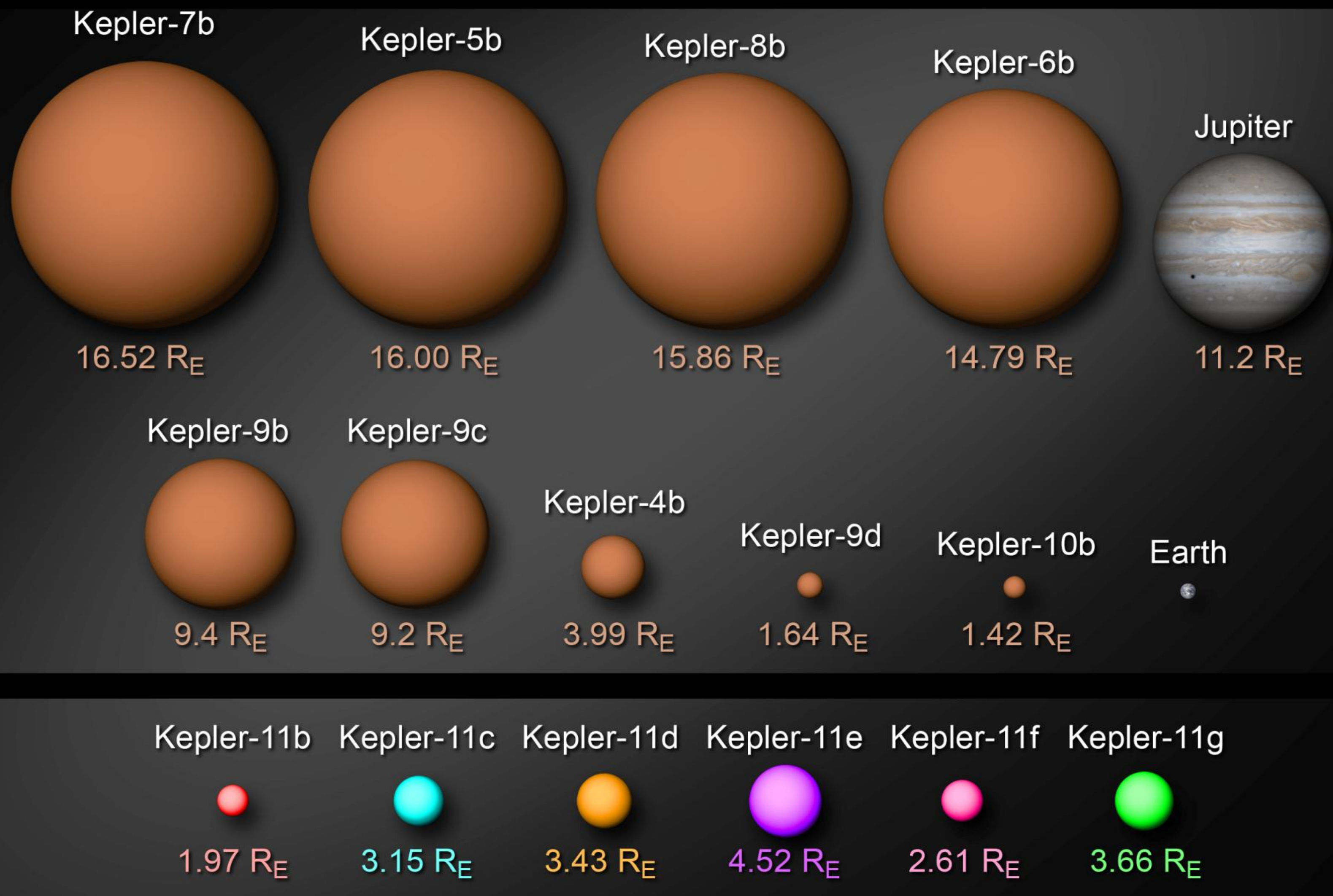


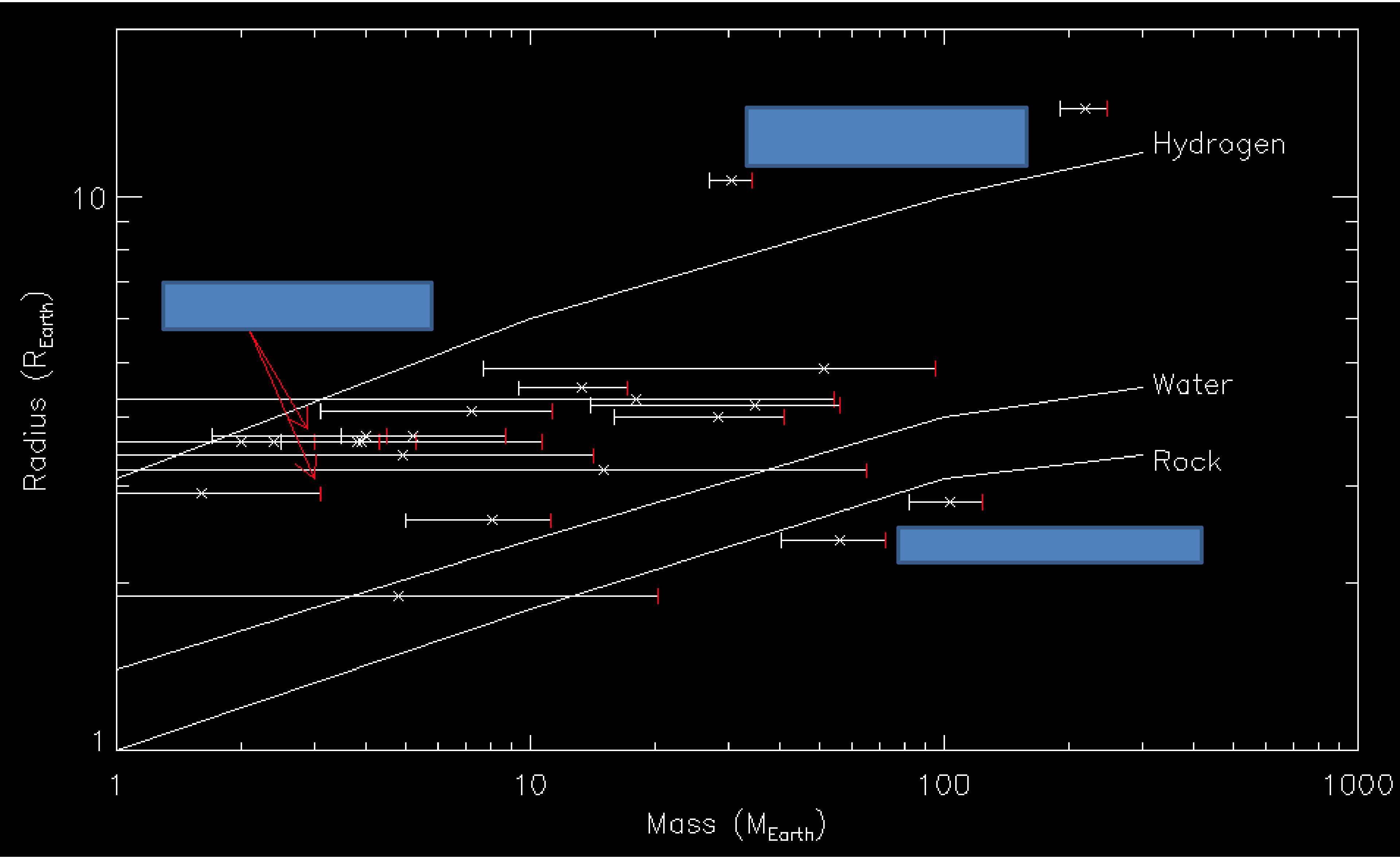
Many systems show gravitational interactions (transit time variations), which can be used to constrain planet masses and bulk densities.

Composition of Kepler-11 Planets

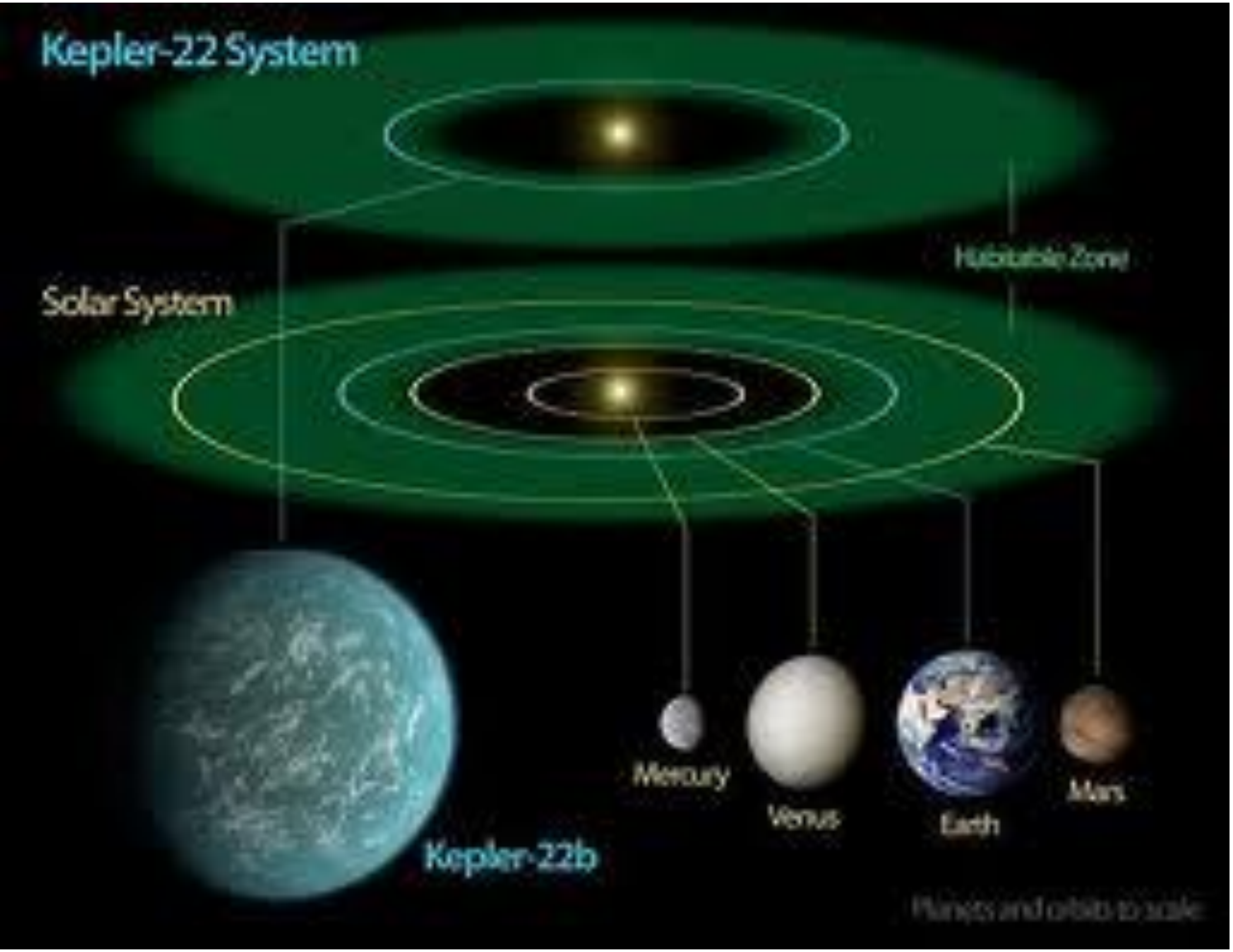


Planet Sizes



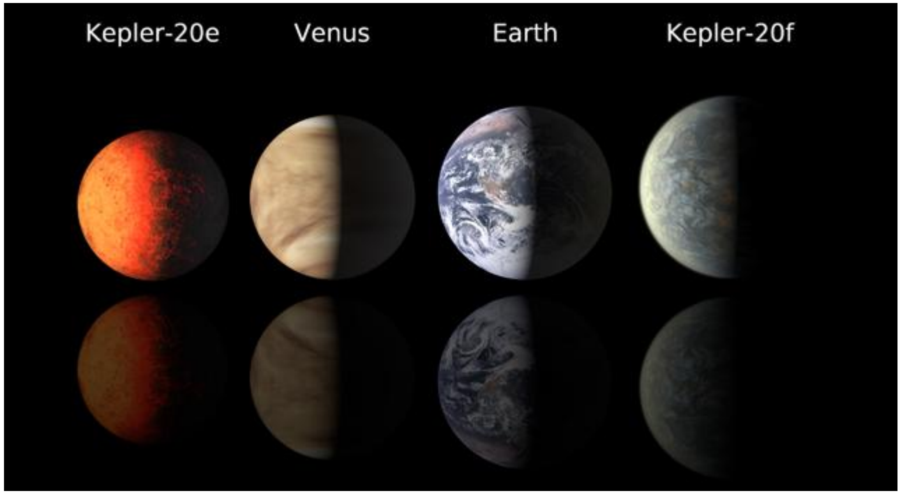

Hydrogen
Water
Rock
10
1
1
10
100
1000
Radius (R_{Earth})
Mass (M_{Earth})

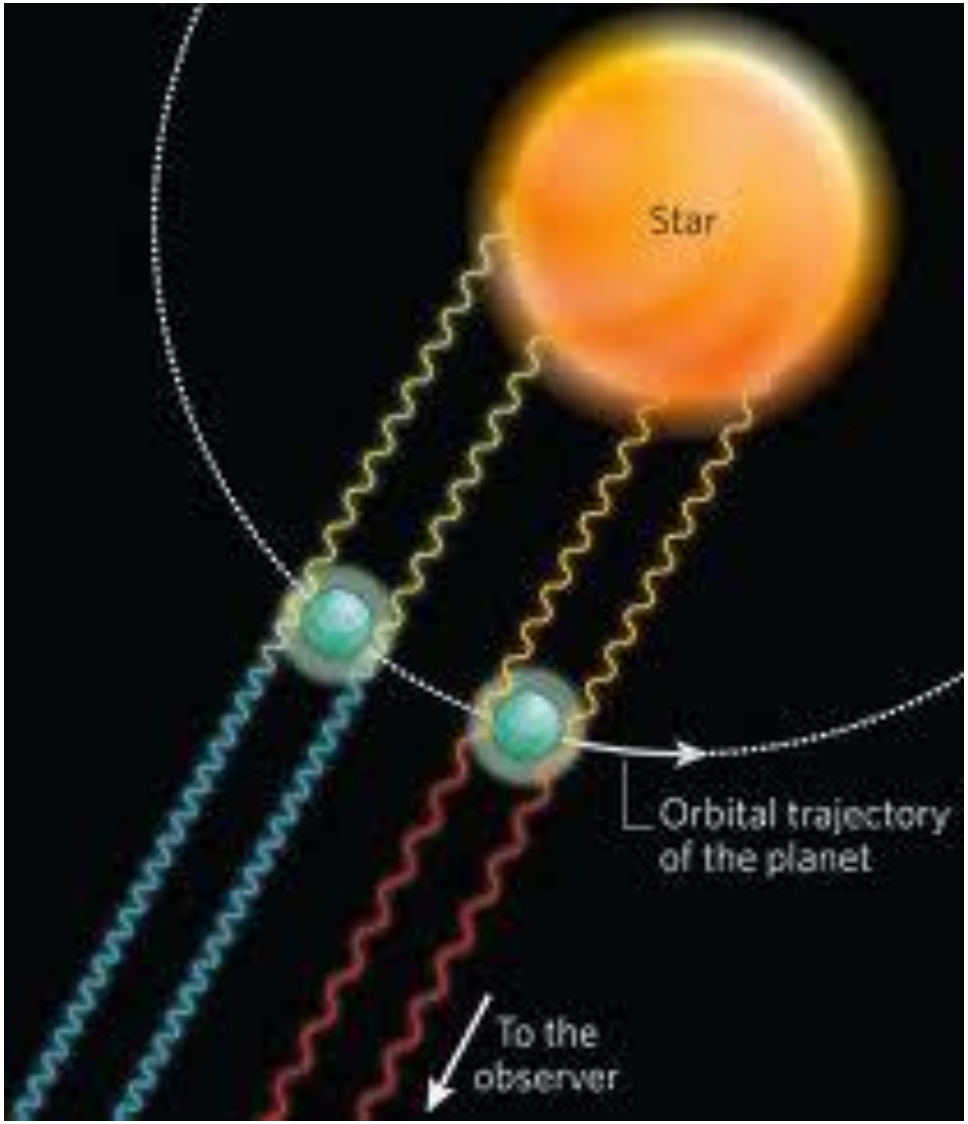
Kepler-22 b
קפלר 22b



האיזור הישיב

Kepler-20e

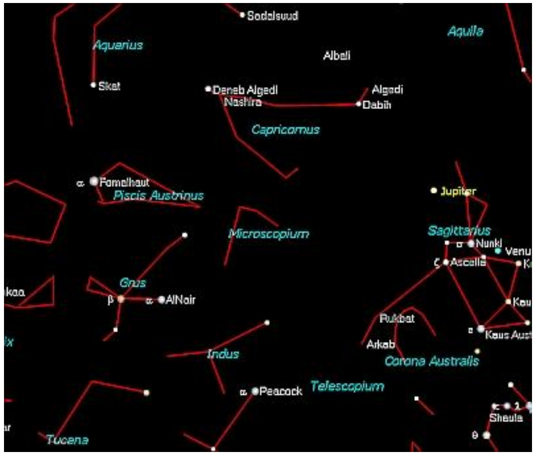


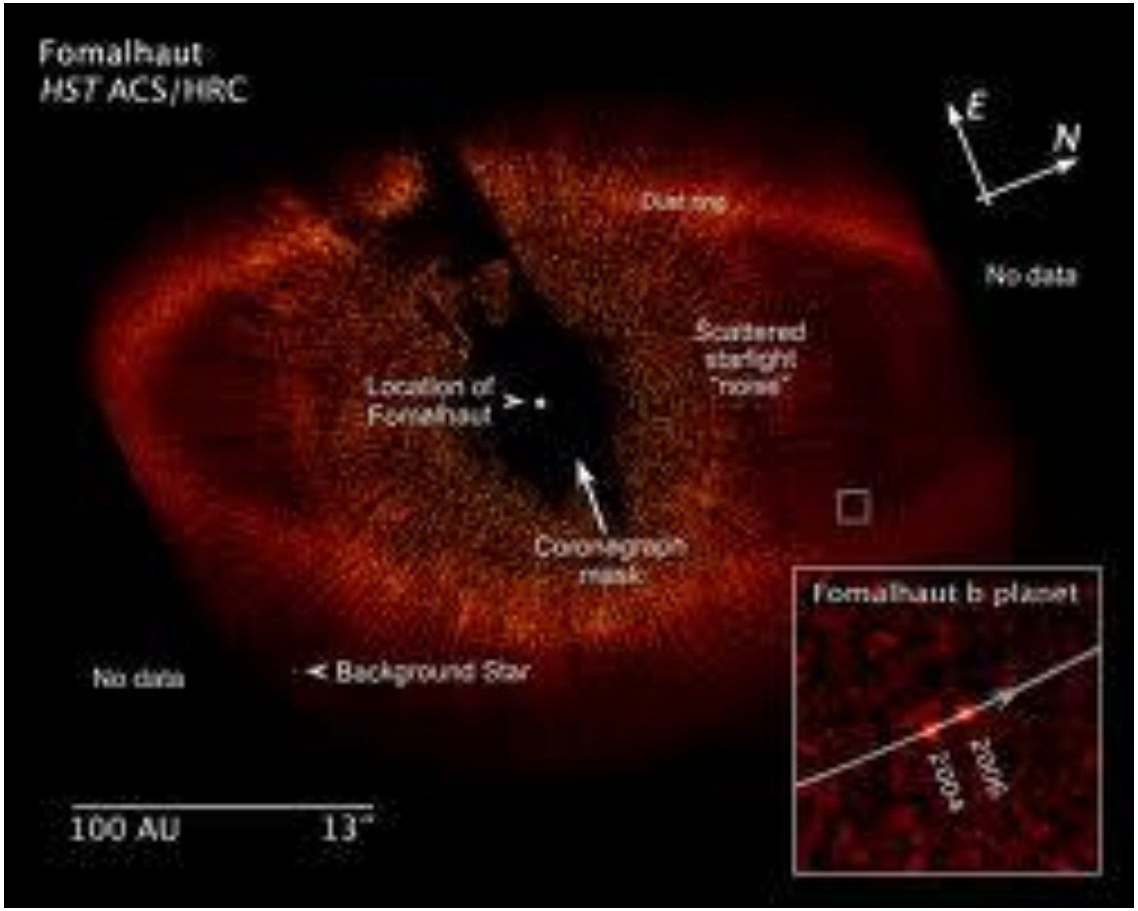

Star
Orbital trajectory
of the planet
To the
observer

תמונה ראשונה של כוכב לכת מחוץ למערכת השמש

פי הלויתן (אלפא בדג דרומי)

Fomalhaut

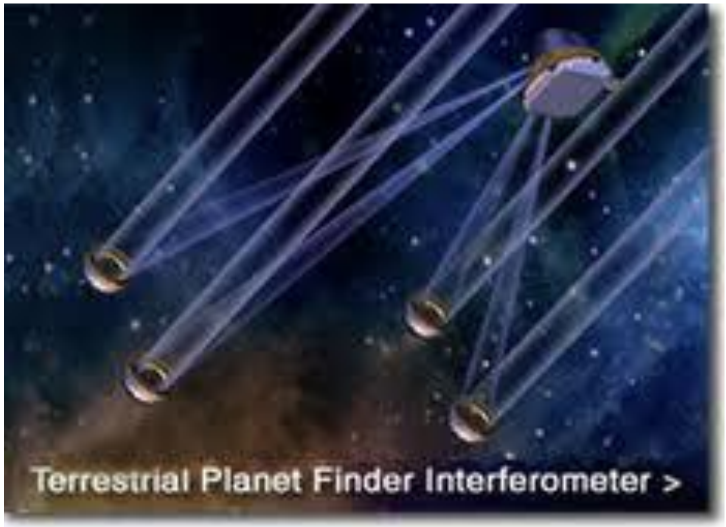




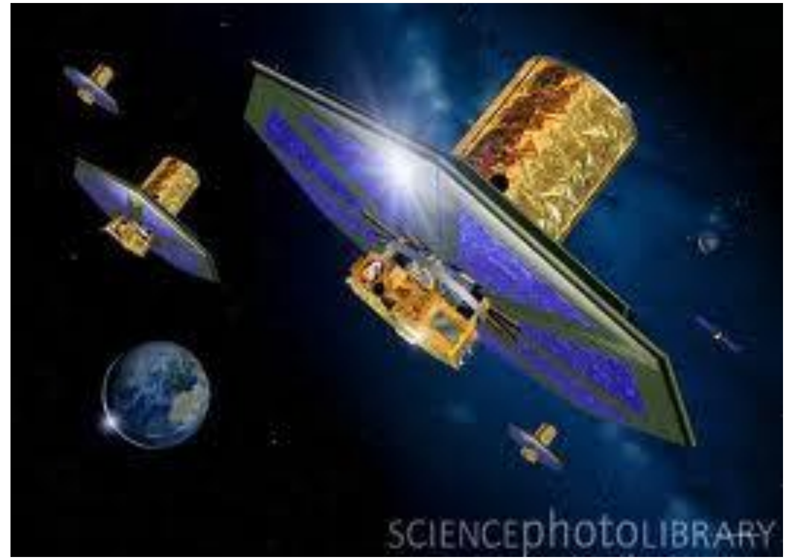
25 שנות אור

115 יחידות אסטרונומיות

TPF


Terrestrial Planet Finder Interferometer >

Darwin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