系外惑星 exoplanets

An exoplanet or extrasolar planet is a planet outside of our solar system that orbits a star.

1. Introduction (discovery of exoplanets)
2. How to identify exoplanets
    2-1. Transit photometry
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History of discoveries

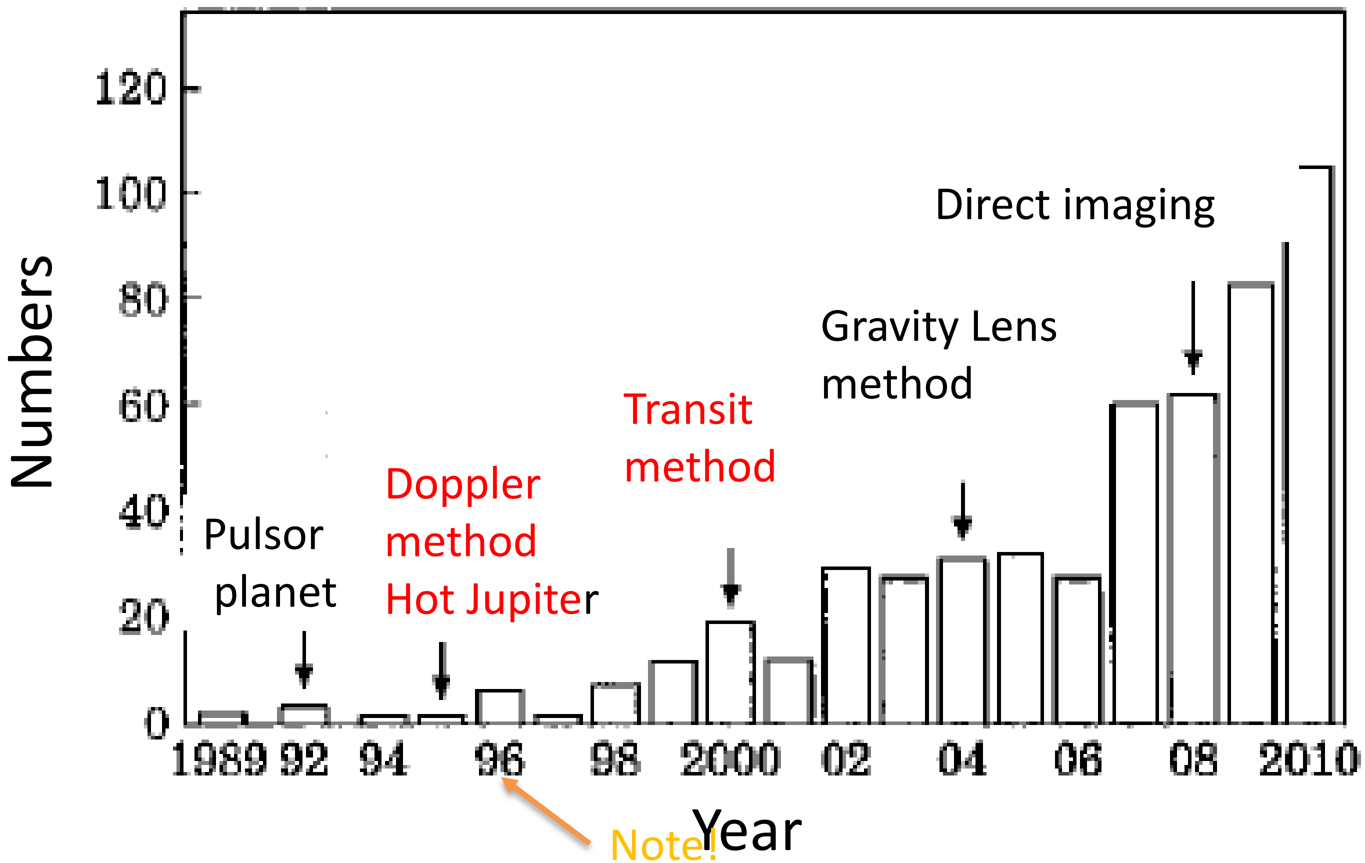
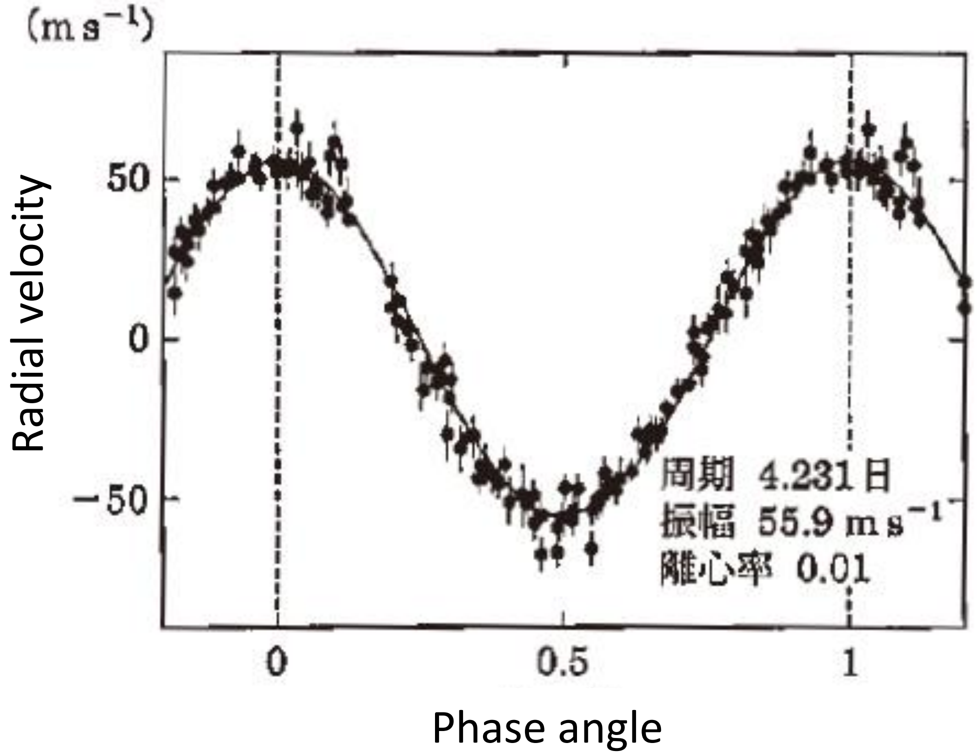


Fig. The number of discoveries of exoplanets in each year (from 1989 to 2010). Since the successful measurement in 1995 by *Mayor*, they had believed that Giant planets would have orbited far away from massive central stars with long orbital periods. Little possibility to cross the star. However, it has turned out that is not true.

51 Peg b (Mayor & Queoz, 1998)

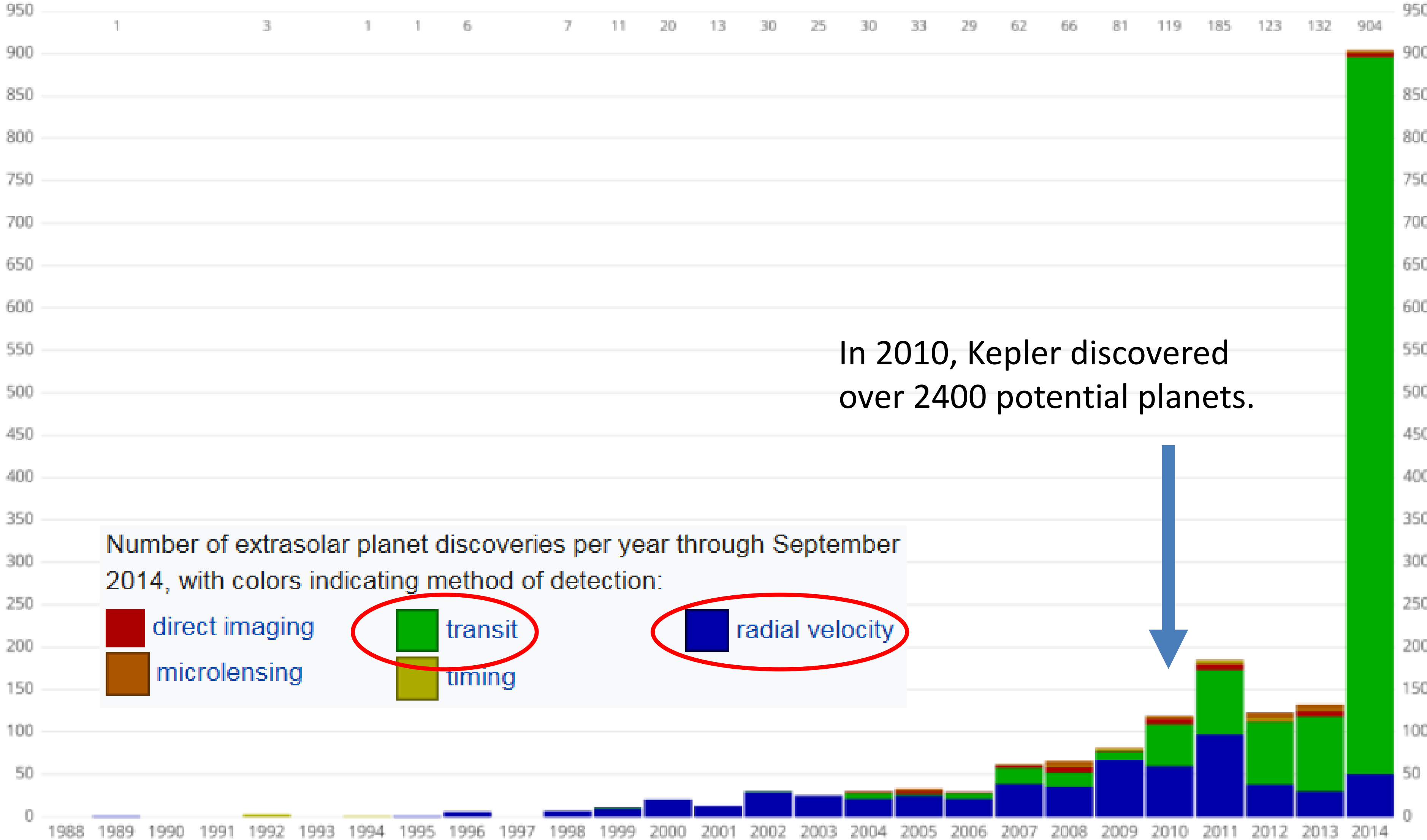


P=4 days,
m=0.5MJ

Hot Jupiter

Fig. The first (surely) success of identifying an exoplanet. Cf. Jupiter: 10 m/s, Earth 10cm/s

The number of discoveries is increasing rapidly (AFT 2010)

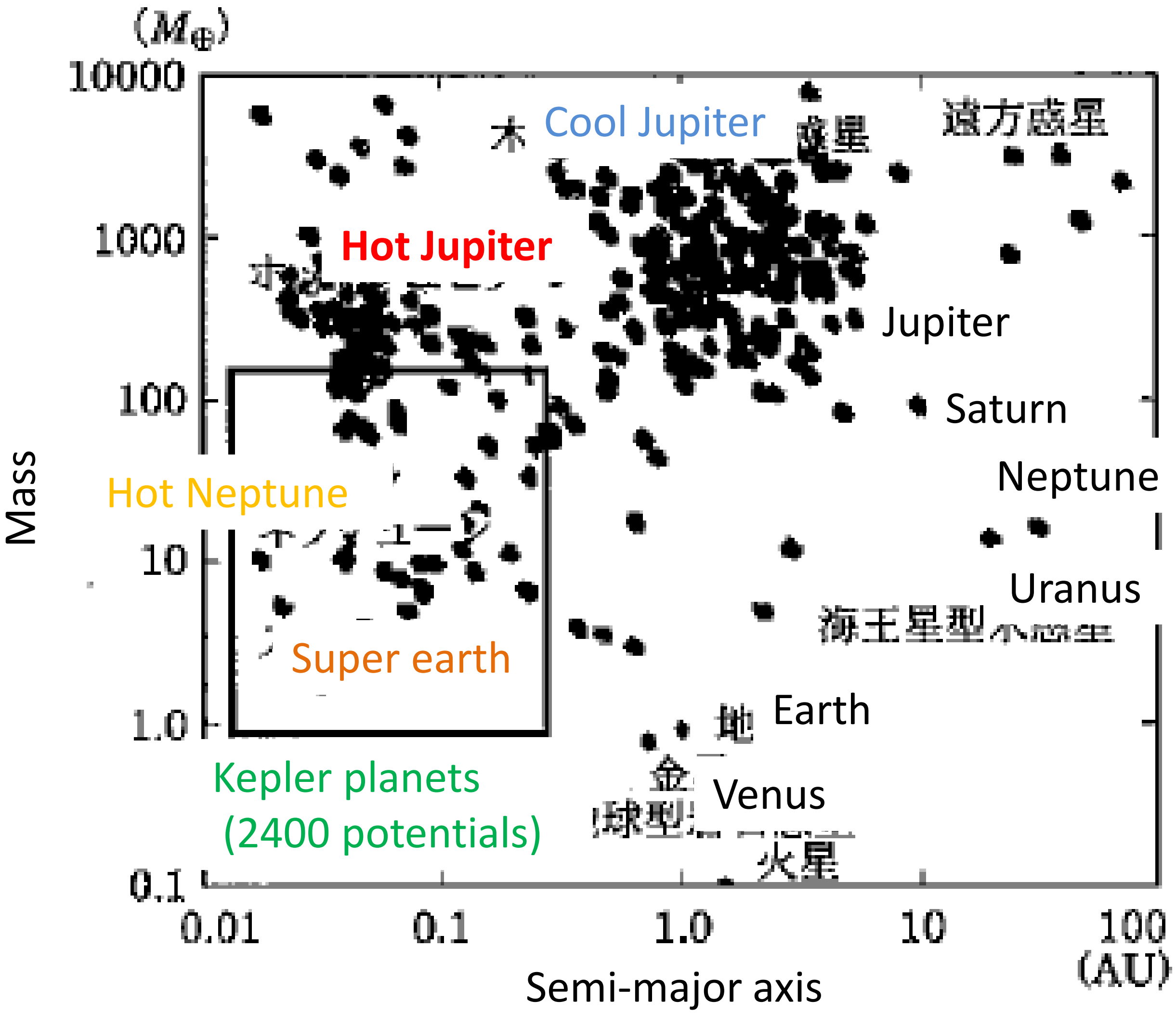


Why is the number of discoveries increasing recently?

Technological development?

➔ No! On those days, they believed that Exoplanets were like Jupiter in the solar system. Such a prejudice delays the discovery.

Categorization



Hot Jupiter: surprising !
Mass ～ M_J
r<0.1AU

Hot Neptune:
Mass ～ 0.1 M_J
r<0.1AU

Kepler planets:
Kepler satellite found over 2400 exoplanets, but they need to be verified by another method. They are potentials.

Super Earth:
Mass 1-10 M_E
r <0.1 AU

Hot Jupiters, hot Neptunes, and super Earths are new categories of planets, while cool Jupiters are also observable.

Focus on the discoveries by Kepler satellite

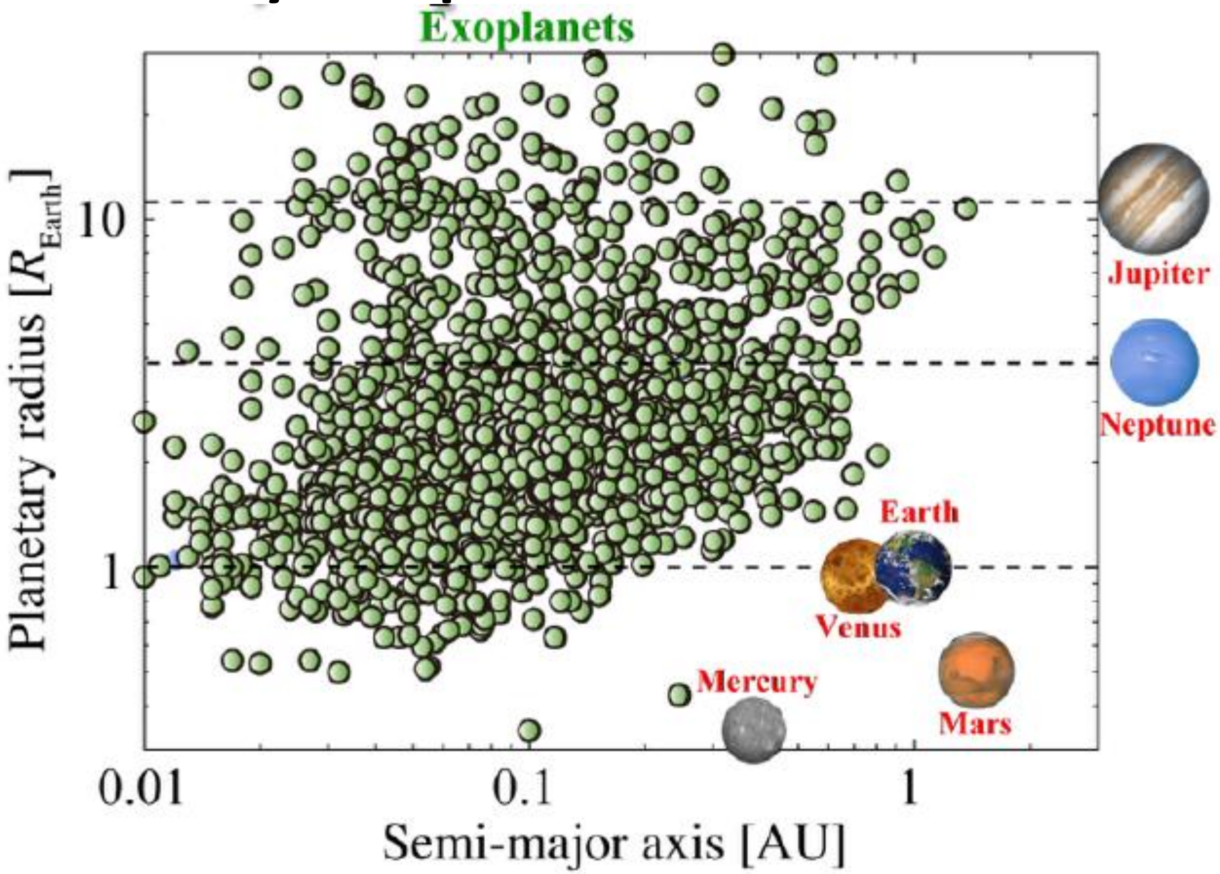


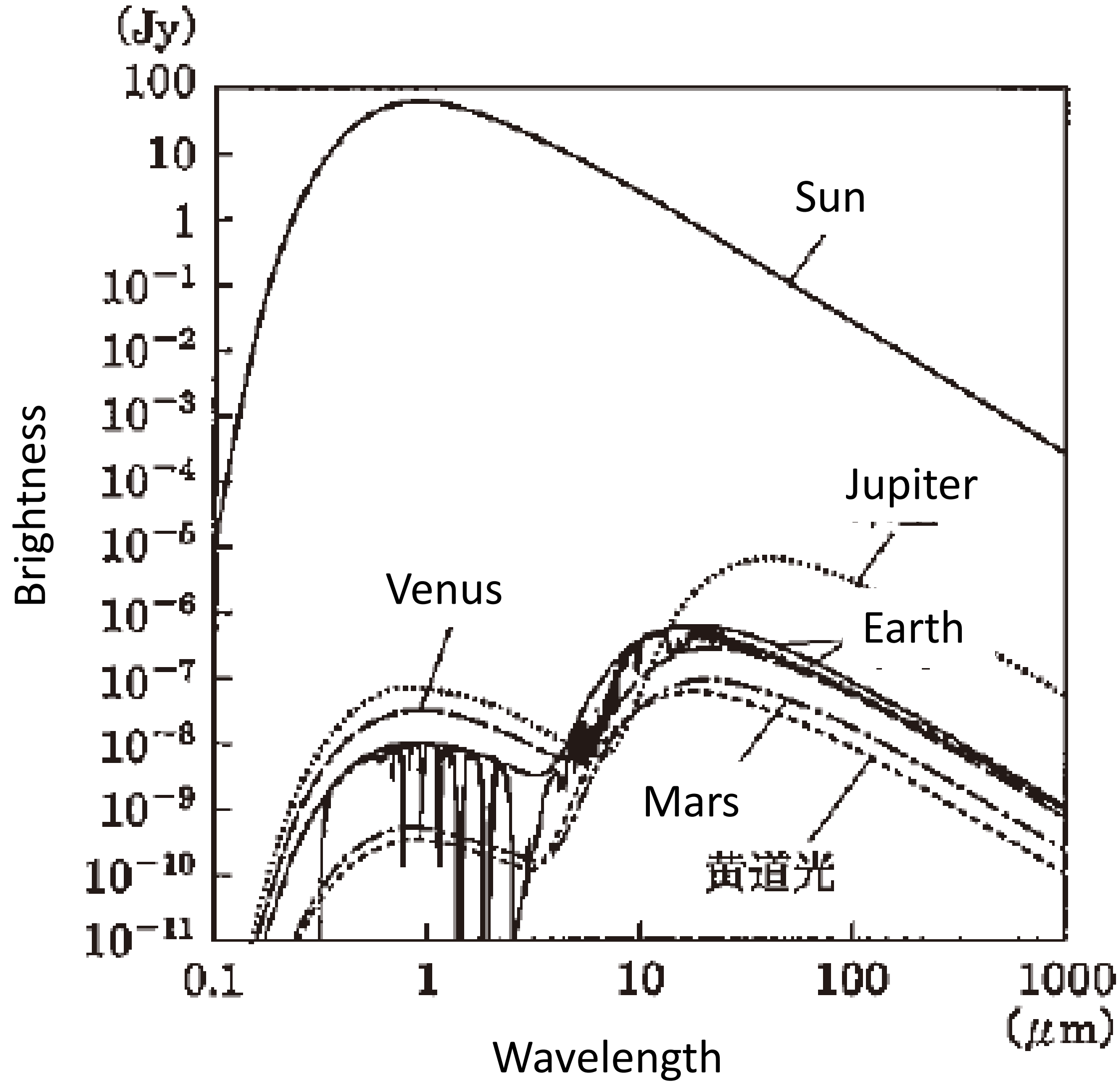
Fig. There is no boundary and no group. Relatively small bodies are main population. This is REAL, because this observation technique has a tendency to detect large (massive) body (shown later).

By the way..

Can Aliens discover our Earth?

Suppose that they live on a planet at 10 pc (3 light-year distance)away from Earth

Can Aliens discover our Earth?
(ref.「太陽系と惑星」)



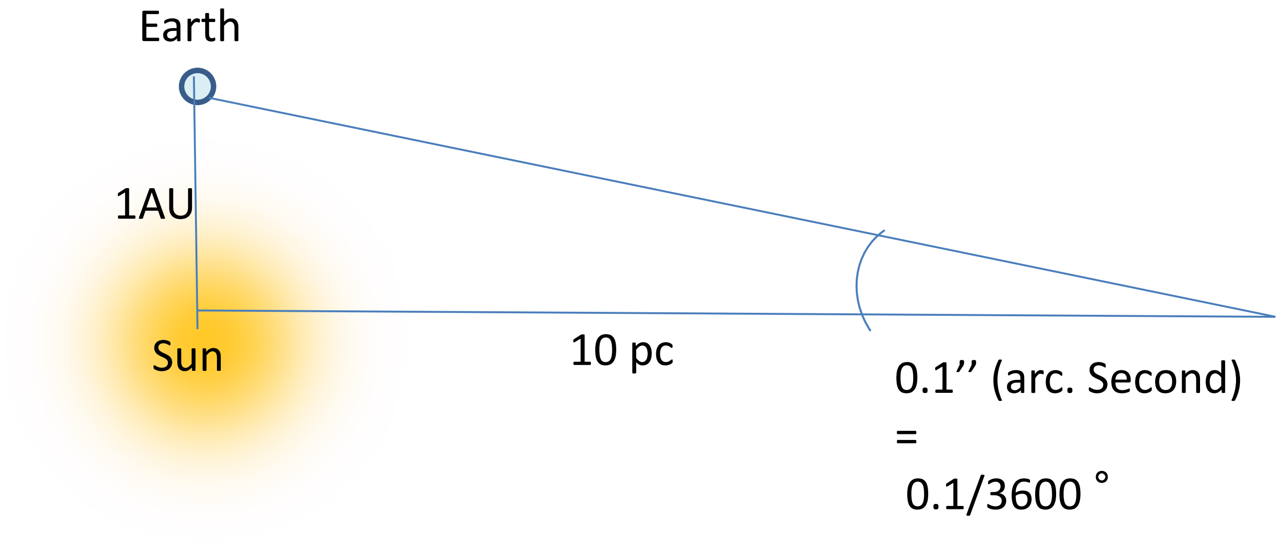
Answer is
"it seems Impossible to see our planet"

Remarks.

Earth has 29 visual magnitude of brightness.

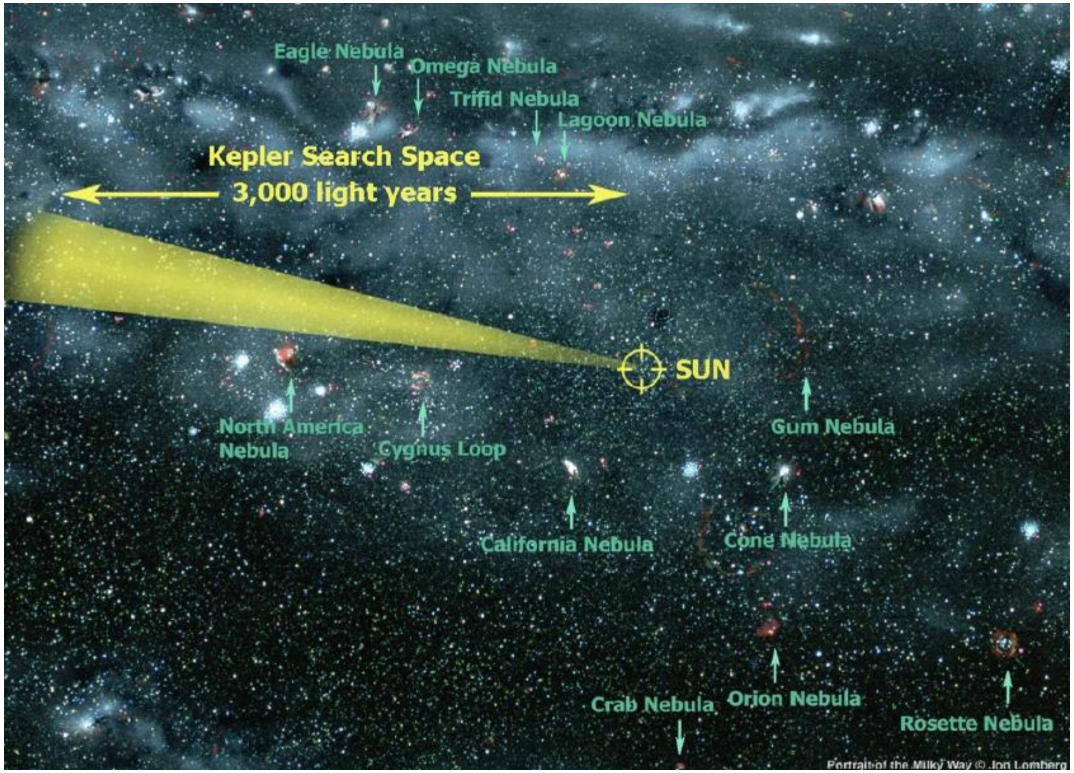
Solar planets' brightnesses are in wide range (over order of 9).

Our planet is very close to Sun.



(Remark) There is no optical instrument enough to find Earth-like exoplanets (in the present). Direct identification (direct imaging) is impossible for discovery of the Earth-like exoplanets.

Direct imaging (detection) seems impossible.



Indirect detections are remaining candidates for findings.

系外惑星 (exoplanets)

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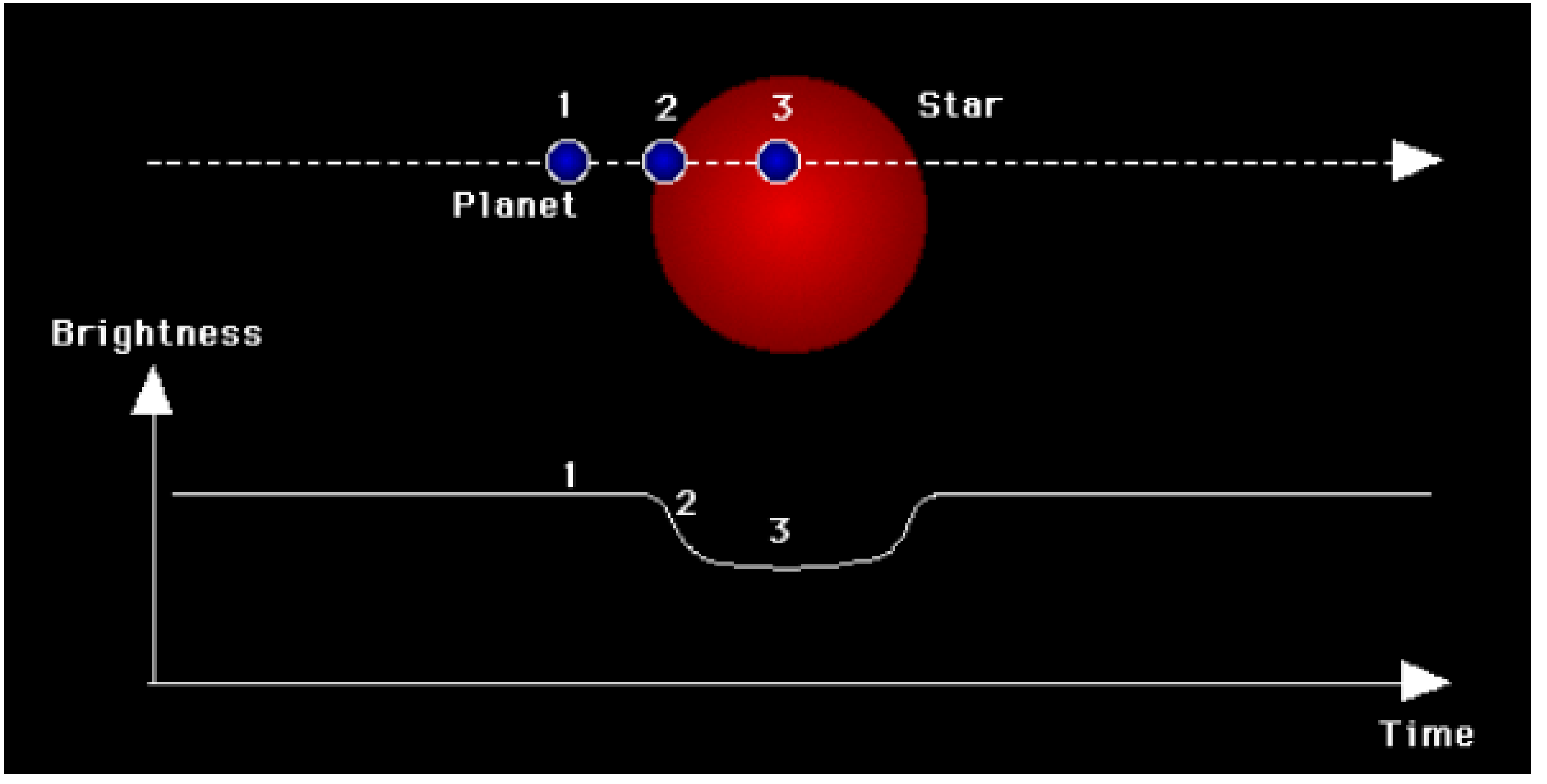
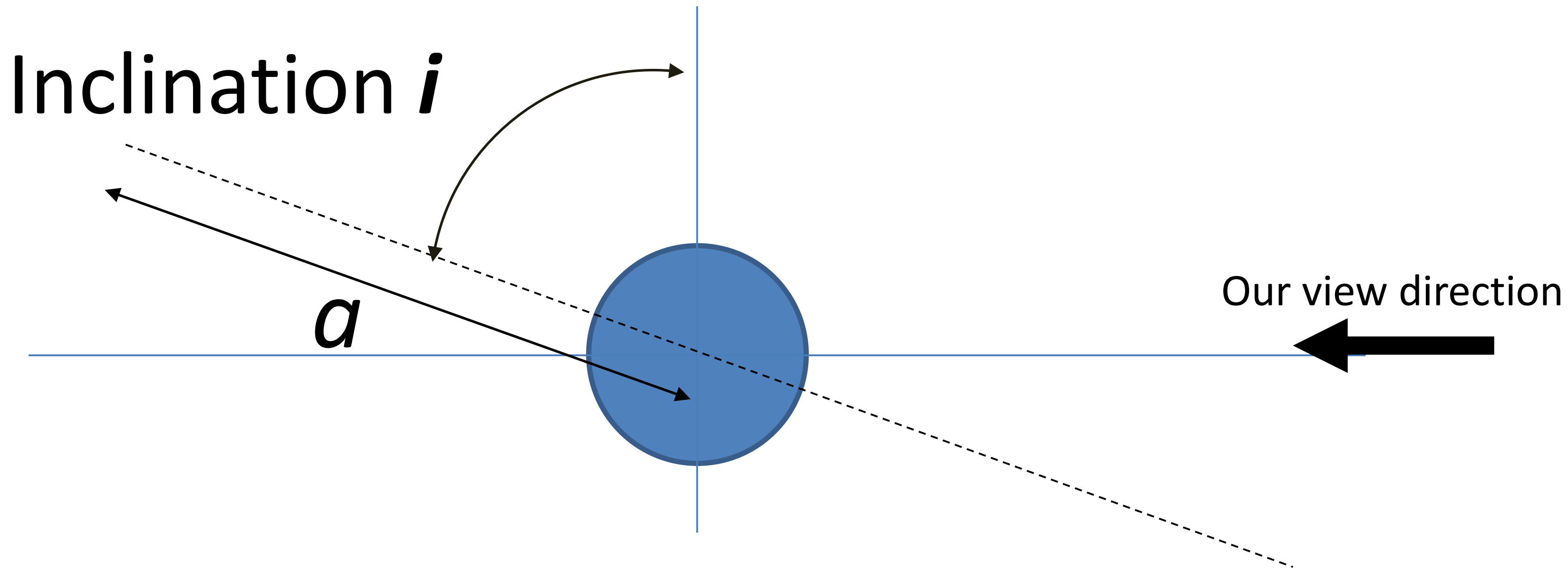
How can we know the existence of the (light/small) body around the (massive/large) star without watching it?

Transit photometry (Transit method)



Transit method



If we are on the orbital plane of the exoplanet, transit surely occurs. If $\boldsymbol{i}$ is enough small, no transit occurs.

$$a \cos \boldsymbol{i} < \boldsymbol{R} + \boldsymbol{r}$$

is necessary condition.

Transit method

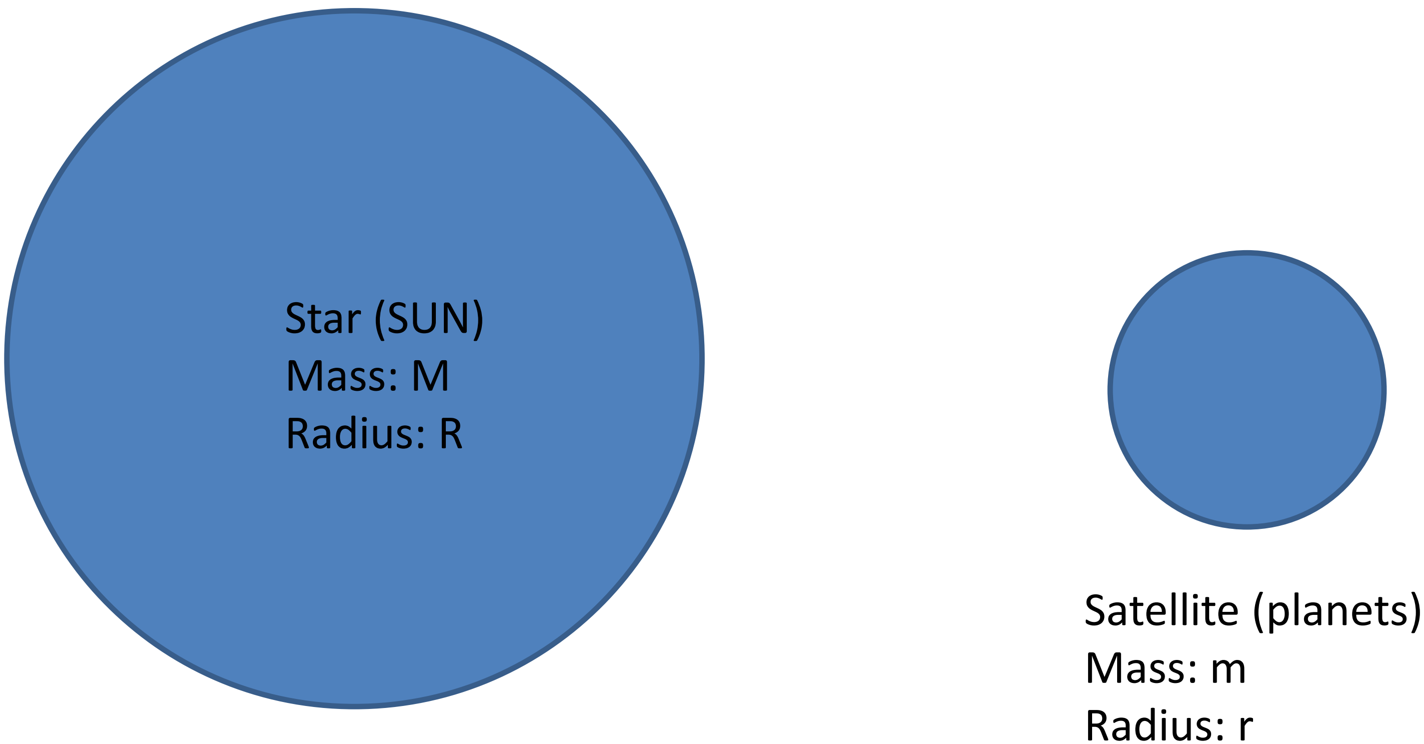
Possibility of transit =

$$\int_0^{R+r/a} d(\cos i) = (r+R)/a$$
$$= R/a$$

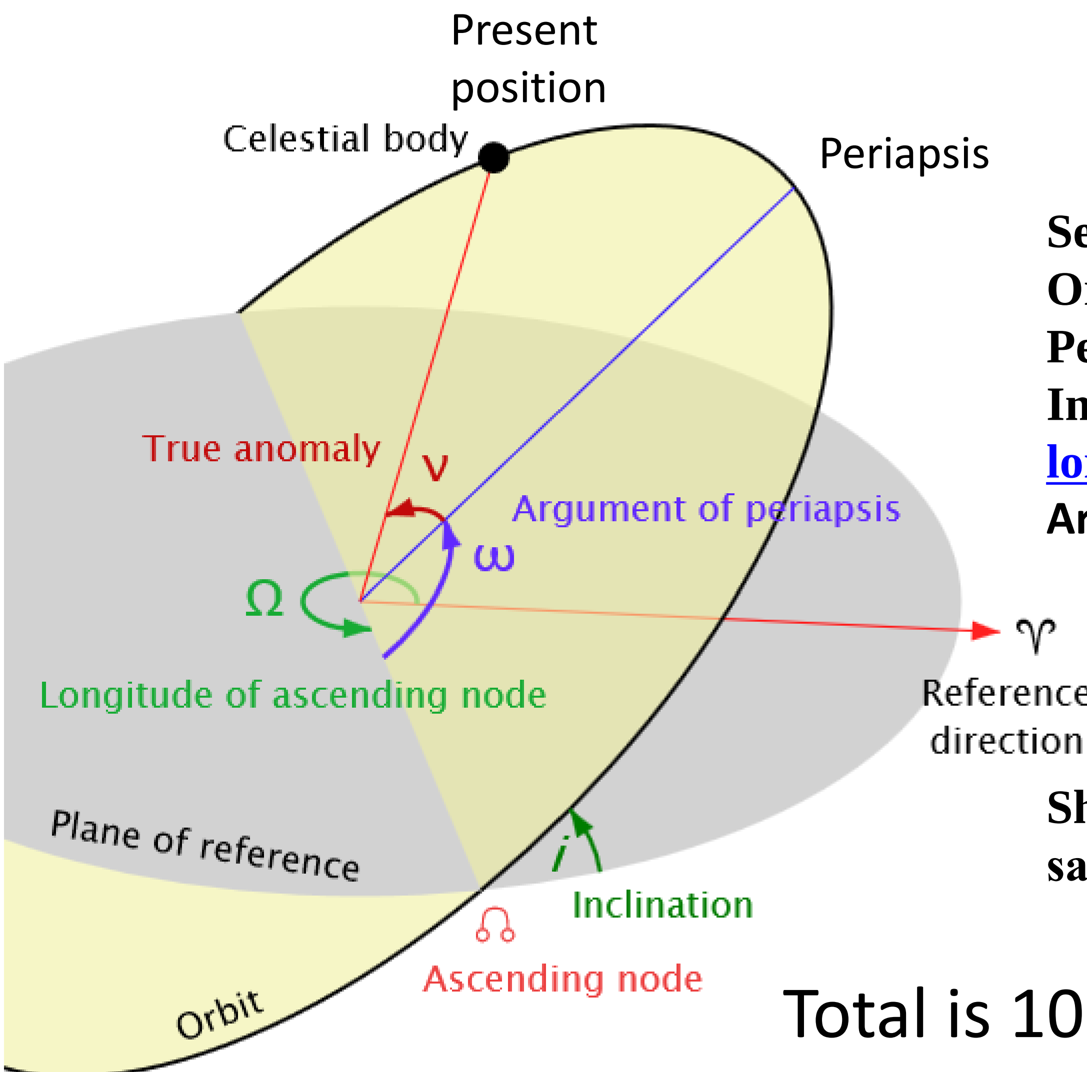
$(R>>r)$

Remark. Planets with a large star & short orbital axis are biased (easier to be found) in this method. That means "HOT JUPITER" is more easily observed than "COOL planets"

What kind of parameters can be obtain?



What kind of parameters can be obtain?



Orbital 6 elements

Semi-Major axis. a
Orbital eccentricity e
Period P
Inclination I,
longitude of the ascending node, Ω
Argument of periapsis ω

Showing present position of satellite: True anomaly angle θ

Total is 10 parameters.

Which parameters can be derived?

What kind of parameters can be obtain?

Transit method assumes that

M, *F* (radiance, brightness of the star) and *R* are already known. (measured by another method or modellings)

According to the transit data, duration (τ)and period (P) are measured.

M,F,R (already known)+ P, τ (if measured)

-> r, a, cos*i*

Exercise

1　太陽系以外の惑星系に関する以下の問Ⅰと問Ⅱに答えよ。

問Ⅰ　ある恒星が惑星を持ち，我々がその惑星の公転面をほぼ真横から見る位置にいる場合，惑星が恒星の手前を通過すると恒星の光をわずかに隠す。これを恒星面通過という。現在の望遠鏡の能力では，恒星は広がりのない点状にしか見えず，惑星は直接見ることすらできない。しかし，恒星面通過を観測することで，惑星の存在が確認でき，加えてその大きさや公転周期が推定できる。恒星面通過は太陽系以外の惑星系を探るための重要な現象である。

恒星Ｓと惑星Ｘからなる惑星系がある。惑星Ｘは恒星Ｓを中心とする半径 a の円軌道を公転しており，恒星Ｓの万有引力による加速度 GM/a^2 と遠心力による加速度 V^2/a とがつりあっている。ここで G は万有引力定数，M は恒星Ｓの質量，V は惑星Ｘの公転の速さである。恒星Ｓは惑星Ｘよりはるかに重いため，静止していると考えてよい。惑星Ｘは光を出さない球とみなすことができ，恒星Ｓの手前を通過する際は，自身と重なる部分の恒星表面からの光を完全にさえぎる。

地球から恒星Ｓの明るさ（放射エネルギー）を測定したところ，図１－１に示すように，惑星Ｘの恒星面通過により，周期 $P=2.7\times10^{-2}$ 年で，$\Delta T=7.0\times10^3$ 秒の間だけ規則的に暗くなることがわかった。相対的な減光量 δ は 1.6×10^{-3} である。ここで δ は，恒星Ｓの通常の明るさを F_1，暗くなっているときの明るさを F_2 として，$\delta=(F_1-F_2)/F_1$ で定義される。図１－２は恒星面通過の際の惑星Ｘの動きの想像図である。恒星Ｓは一様に光る円盤とみなせ，惑星Ｘはその手前をＡ～Ｅのいずれかを通って左から右に横切るものとする。

恒星Ｓは太陽と同じ質量，半径，絶対等級を持つことがわかっている。以下では，地球の公転軌道を半径 1.0 天文単位の円とし，その公転の速さを 3.0×10^4 m/秒，太陽の半径を 7.0×10^8 m，地球から見た太陽の見かけの等級を -26.8 等級，$\log_{10}2=0.301$，$\log_{10}3=0.477$ とせよ。

(1)　惑星Xの公転の速さが $V=1.0\times10^5$ m/秒であることを導け。

(2)　恒星面通過の際の惑星Xの動きとして可能性のあるものを，図1－2のA～Eのうちからすべて選び，その理由を1～2行で示せ。

(3)　惑星Xの半径を有効数字2桁で求めよ。

(4)　惑星Xから見た恒星Sの見かけの等級を小数点以下1桁まで求めよ。

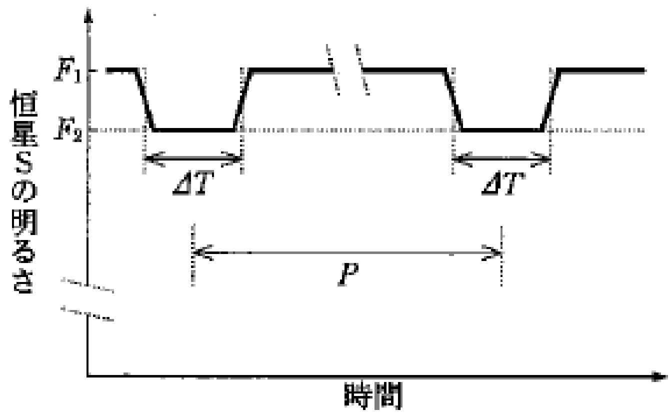


図1－1　恒星Sの明るさの時間変化

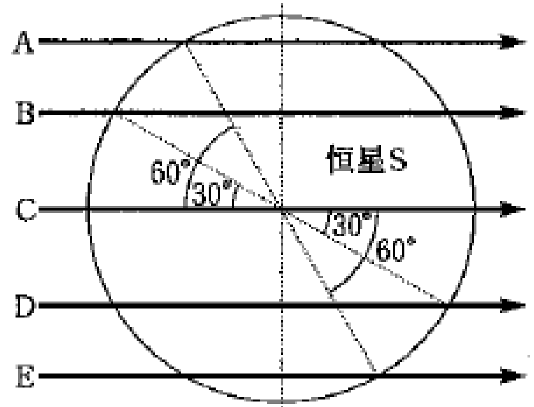


図1－2　恒星面通過の際の惑星Xの動きの想像図。惑星Xは恒星Sの手前をA～Eのいずれかを通って左から右に横切る。Cは恒星Sの中心を通る。

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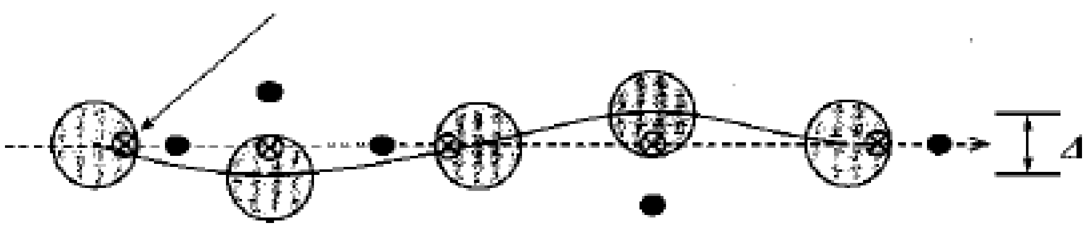
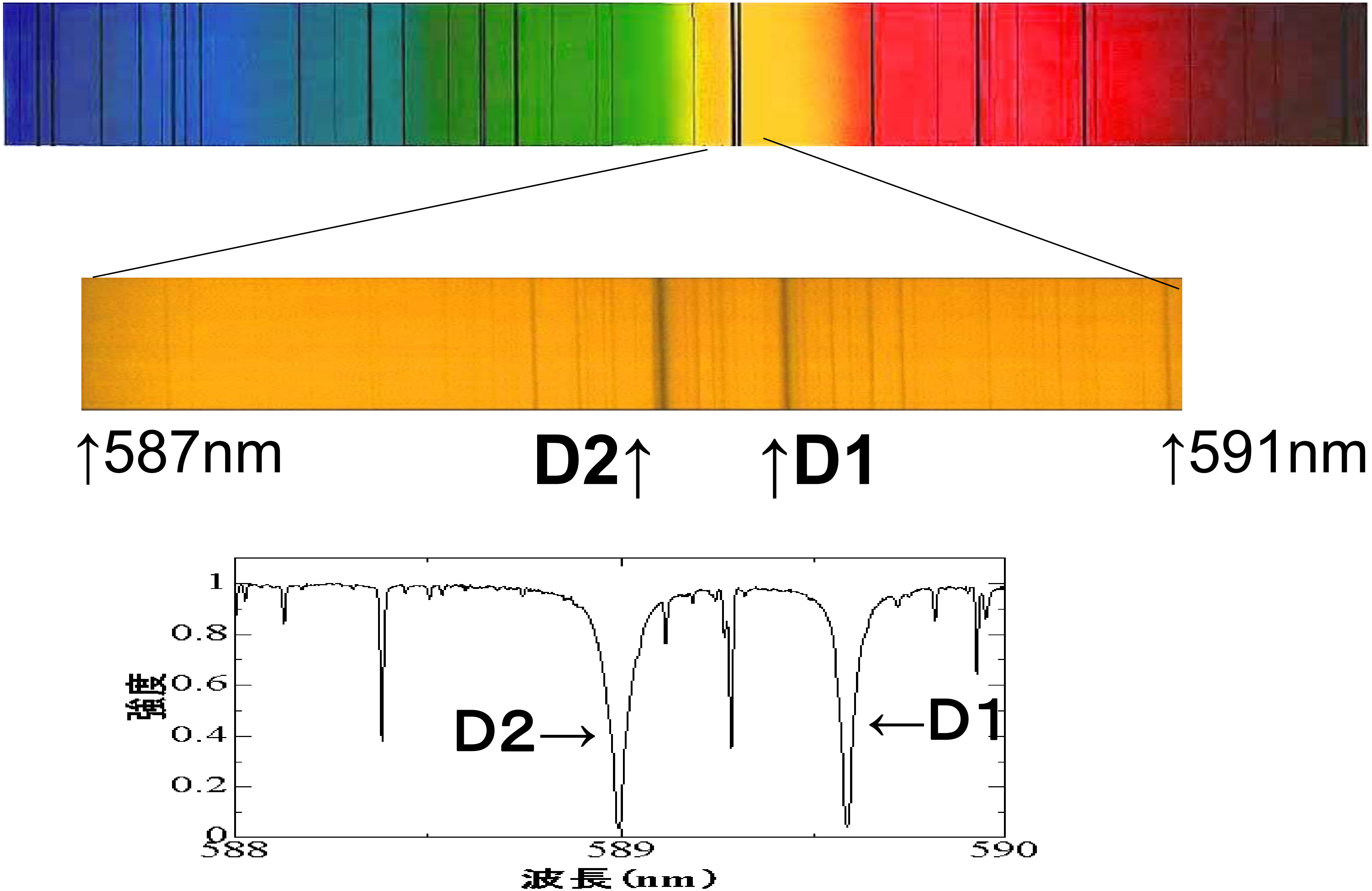
Doppler spectroscopy/Astrometry

- This (astrometry) was based on the precise measurement of the star and it was a main stream in the 20 century. No exoplanet was identified by the astrometry method.
- Doppler spectroscopy was the most successful in the past decade. It measures the velocity of the star based on Doppler shift in the absorption line.

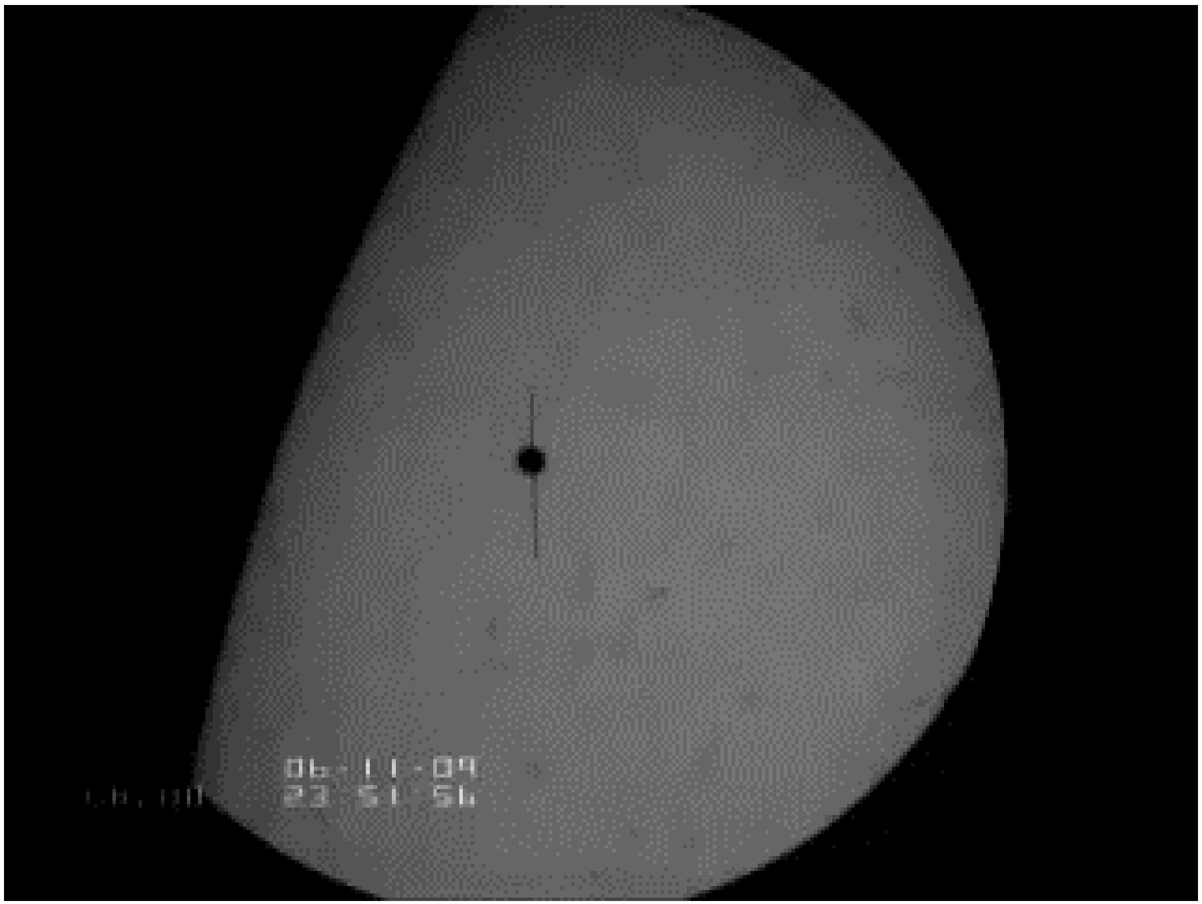
$$\frac{\Delta\lambda}{\lambda} = \frac{V}{c}$$



Solar spectrum (example)

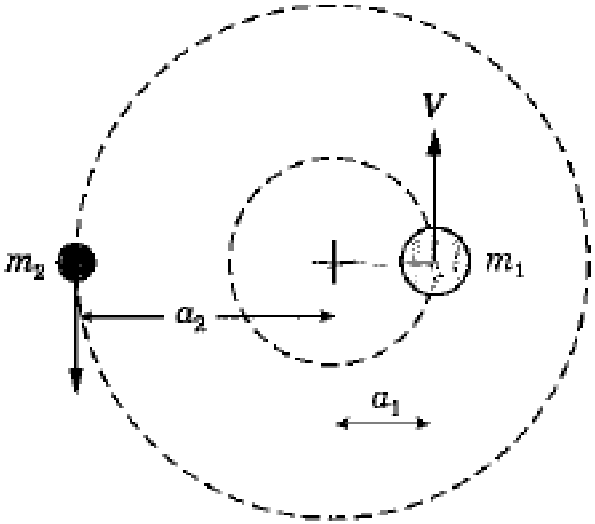


Difficulty on the ground-based observation (ex. Mercury transit across sun)



Even in the lowest-seeing point in Japan (Hida observatory), the see was a few seconds.

Basic (but complicated?) equations



(Q1) Find *K(amplitude of velocity)* in the following the equation. K represents the amplitude of the observed velocity.

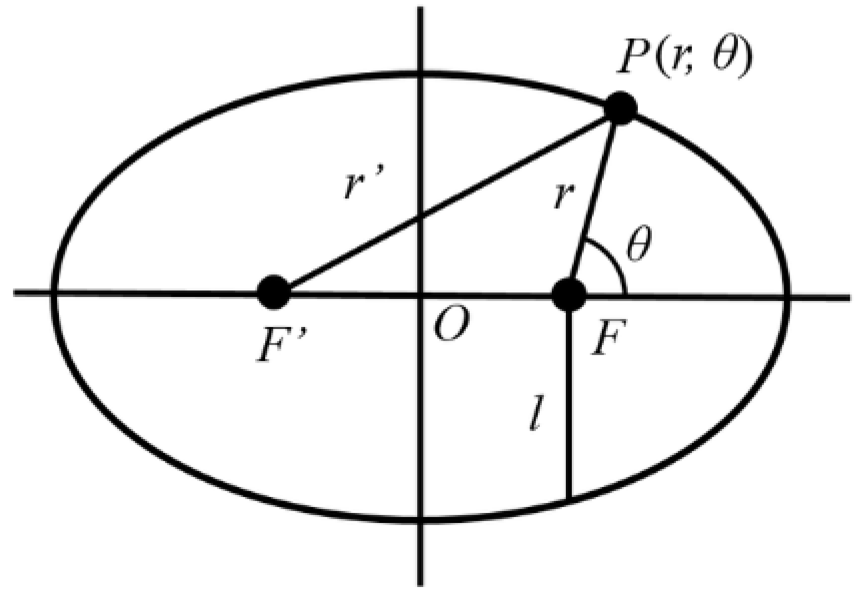
$$V = K\left\{\cos\left(f + \omega\right) + e\cos\omega\right\}$$

f: true anomaly angle
ω: argument of periapsis

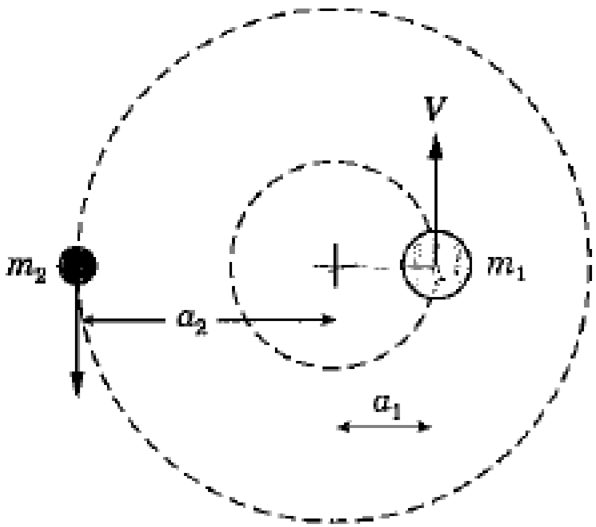
Preparation-1:

(Q) Describe the *ellipse in polar coordinate.*

$$r = \frac{l}{1+e\cos\theta}$$



Prepaeation-3:



Gravity forces between 2 objects are,

$$d^2\boldsymbol{r}_1/dt^2 = -G(m_2/r_{12}{}^3)(\boldsymbol{r}_1-\boldsymbol{r}_2)$$

$$d^2\boldsymbol{r}_2/dt^2 = -G(m_2/r_{12}{}^3)(\boldsymbol{r}_2-\boldsymbol{r}_1)$$

If relative position, $\boldsymbol{r}=\boldsymbol{r}_2-\boldsymbol{r}_1$, is considered,

$$d^2\boldsymbol{r}/dt^2 = -G(m_1 + m_2/r^3)\boldsymbol{r}$$

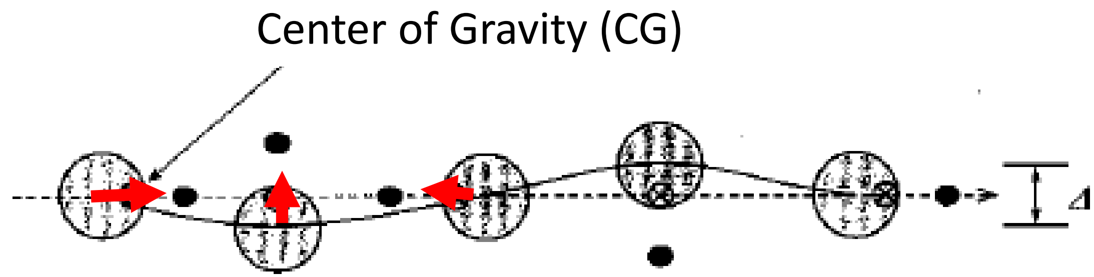
Preparation-3:

Precise Position of massive star (m_1) from us (Earth)

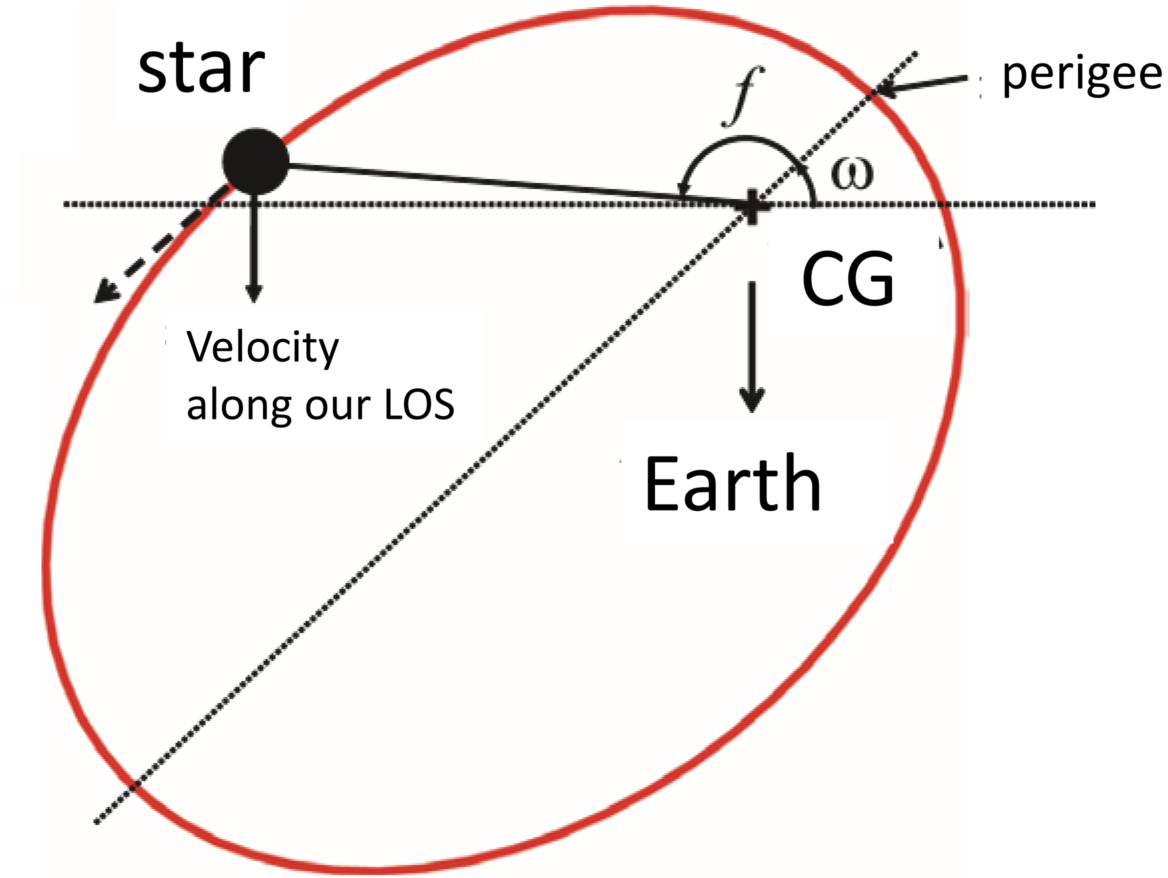
$\vec{R}$ = (CG between m_1 and m_2)

+

$m_2/(m_1+m_2)\,\vec{r}$



Calculate a radial velocity (along the our LOS) of the star



V= (velocity of CG) +
d(r sin(ω+f) x sini) / dt

Please check!!!

$$V = K\left\{\cos\left(f+\omega\right)+e\cos\omega\right\}$$, here K is $a_1 \sin i = (P/2\pi)\sqrt{1-e^2}K$

Basic equation

(Q2) Derive the following the equation. ***K*** represents the amplitude of the observed velocity (as shown in previous page).

$$K = \frac{2\pi}{P}\frac{a_* \sin i}{\sqrt{1-e^2}} = \left(\frac{2\pi G}{P}\right)^{1/3}\frac{1}{\sqrt{1-e^2}}\frac{m_p \sin i}{\left(m_* + m_p\right)^{2/3}}$$

(2) The 3rd law of Kepler, Remember that G is constant over universe.

$$(a_1+a_2)^3=(p/2\pi)^2 G\,(m_1+m_2)$$

(3) 2 bodies are orbiting around the center of mass

[Please write down by yourself]

Among above 3 equations, eliminate a_1 and a_2, then deduce

Doppler spectroscopy

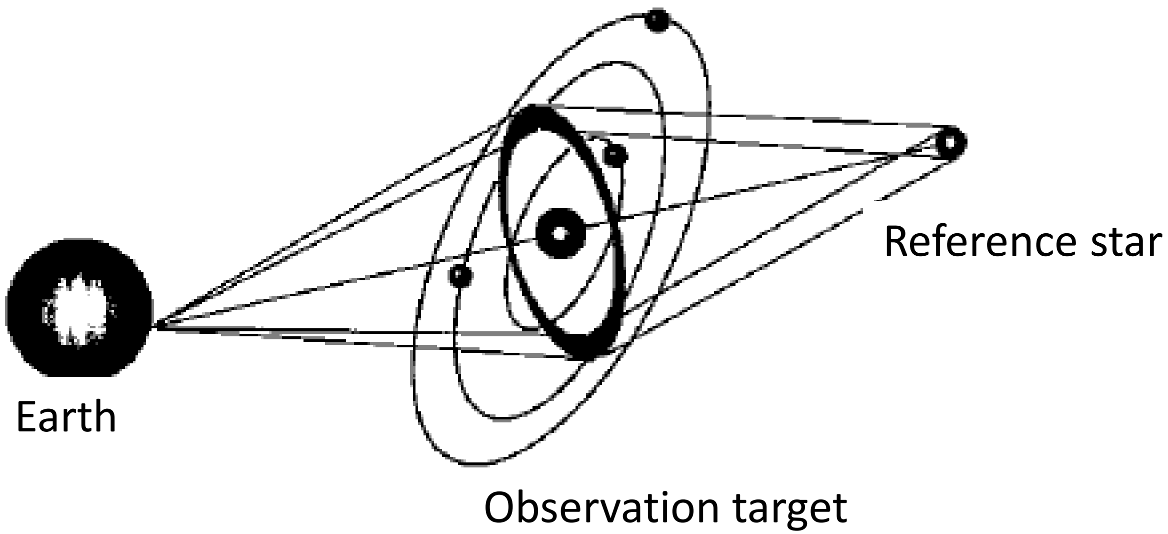
$$m_2 \sin i\ [M_J] = 0.035 (\mathrm{P[yr]})^{1/3} (K_1 [\mathrm{m\,s^{-1}}]) m_1^{2/3}$$

$$K_1 [\mathrm{m\,s^{-1}}] = 28.4 m_2 \sin i\,[M_J] (\mathrm{P[yr]})^{-1/3} m_1 [M_\odot]^{-2/3}$$

Remarks

- (m sin *i)* can be obtained. *(We can only know the lower limit of* m_2, *not* m_2 *itself)*
- *"heavy planet" tends to be identified easily.*
- *"close planet" (hot Jupiter) tends to be identified easily.*
- For Jupiter, *i*=0, P=12 years, m_1=1, m_2=1, then K_1=12m/sec. At the present , the detection limit is 60 cm/s (the maximum resolution).

Gravitational microlensing



Microlensing :A massive object (lens) bends the light path from a bright background object (reference star). This can produce the bright images of the reference star. If the lens-object has an orbiting planet, the light-path is modulated. These deviations allow us to infer the existence of the planet. Deviations typically last a few hours or a few days. The observation seems easy but the needs the continuity.

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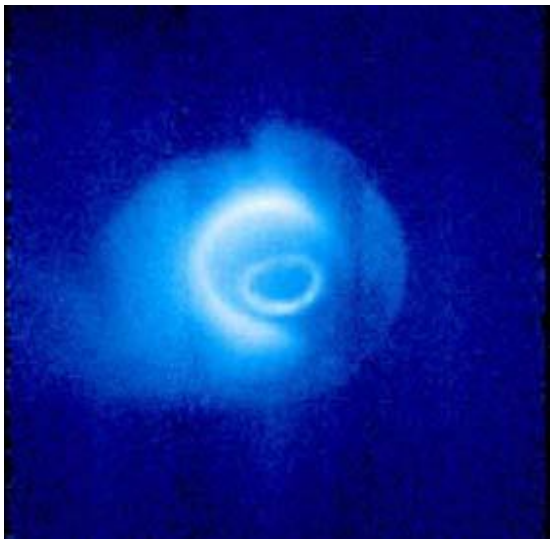
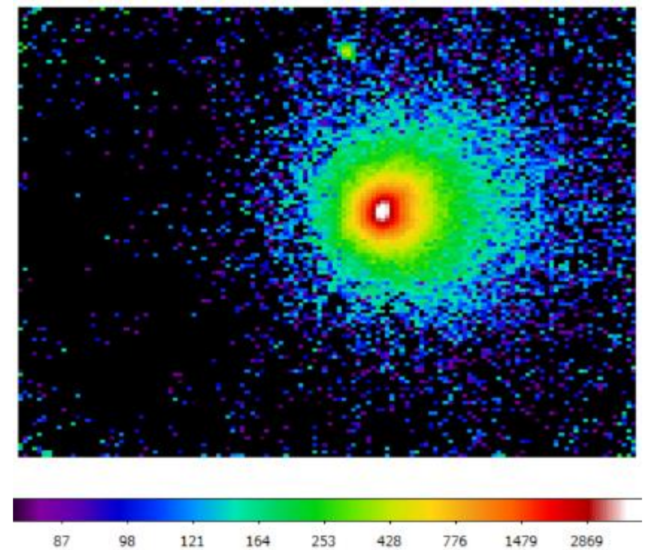
At UV spectral range, star photons are resonantly scattered by exospheric atmosphere.

Earth's outer atmosphere scatters solar lights at 30.4 nm



Earth's hydrogen exosphere expands to more than 100 Re.

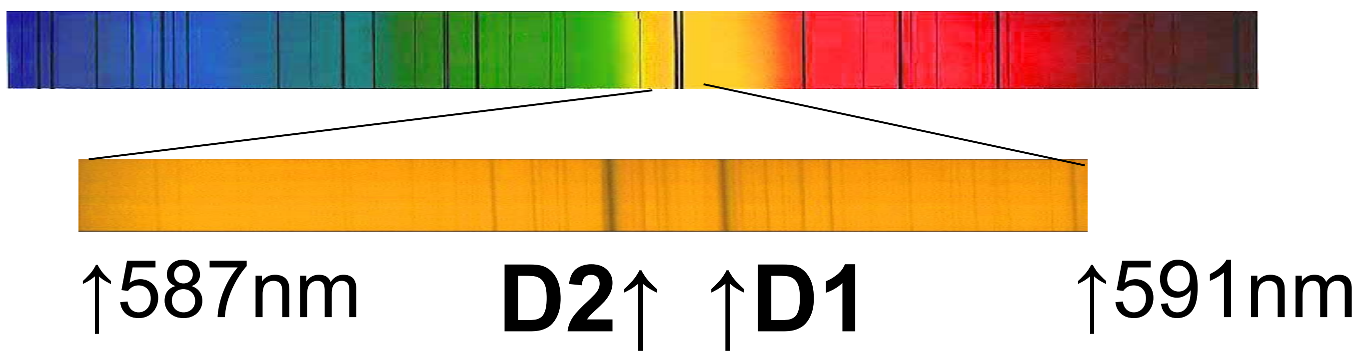


Question. Sometimes dark lines are observed in the spectrum, but sometimes EMISSINOS are measured. What is different each other

Emission of sodium

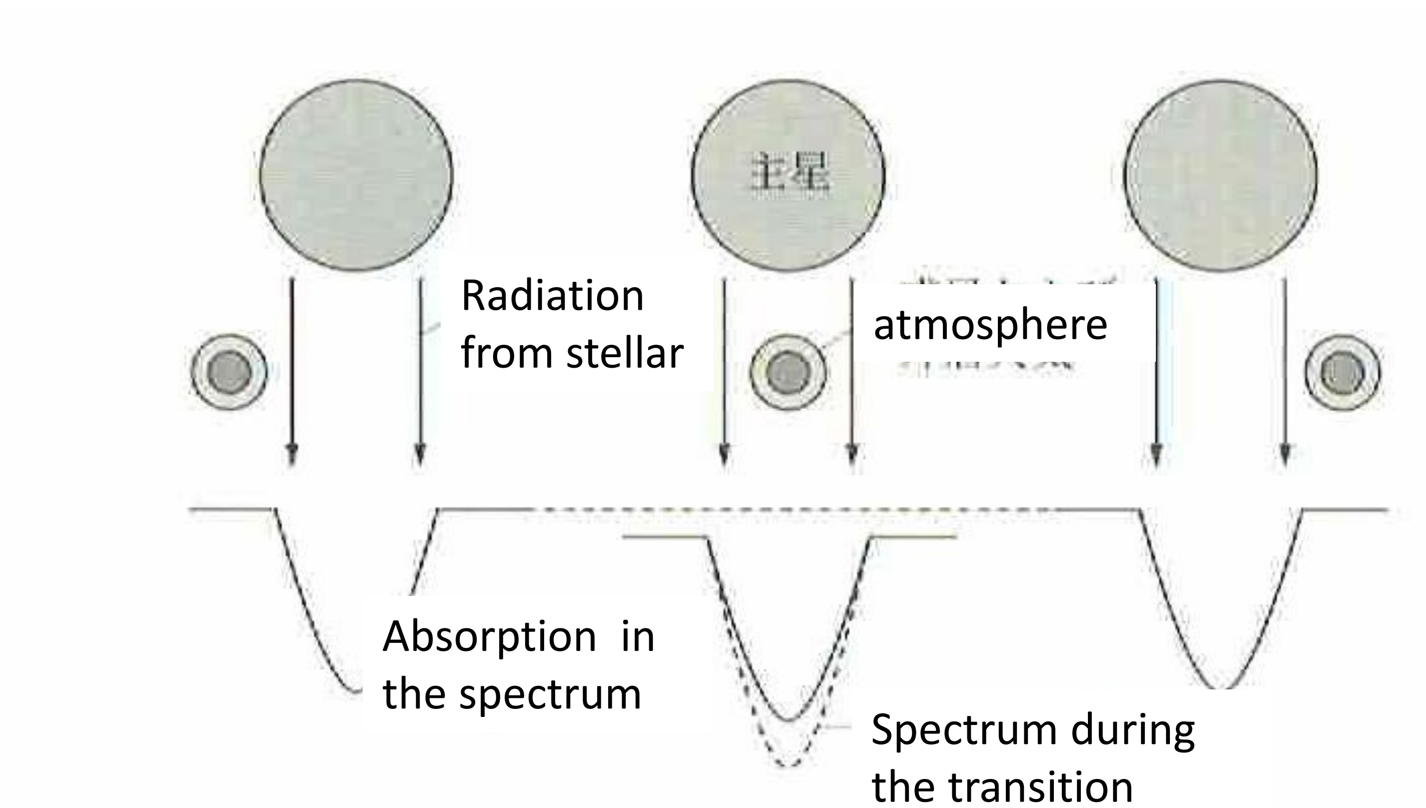
Sodium lamps are commonly used for lights. Sodium gases In the lamp radiate energy as orange-color photons.

Dark lines of sodium

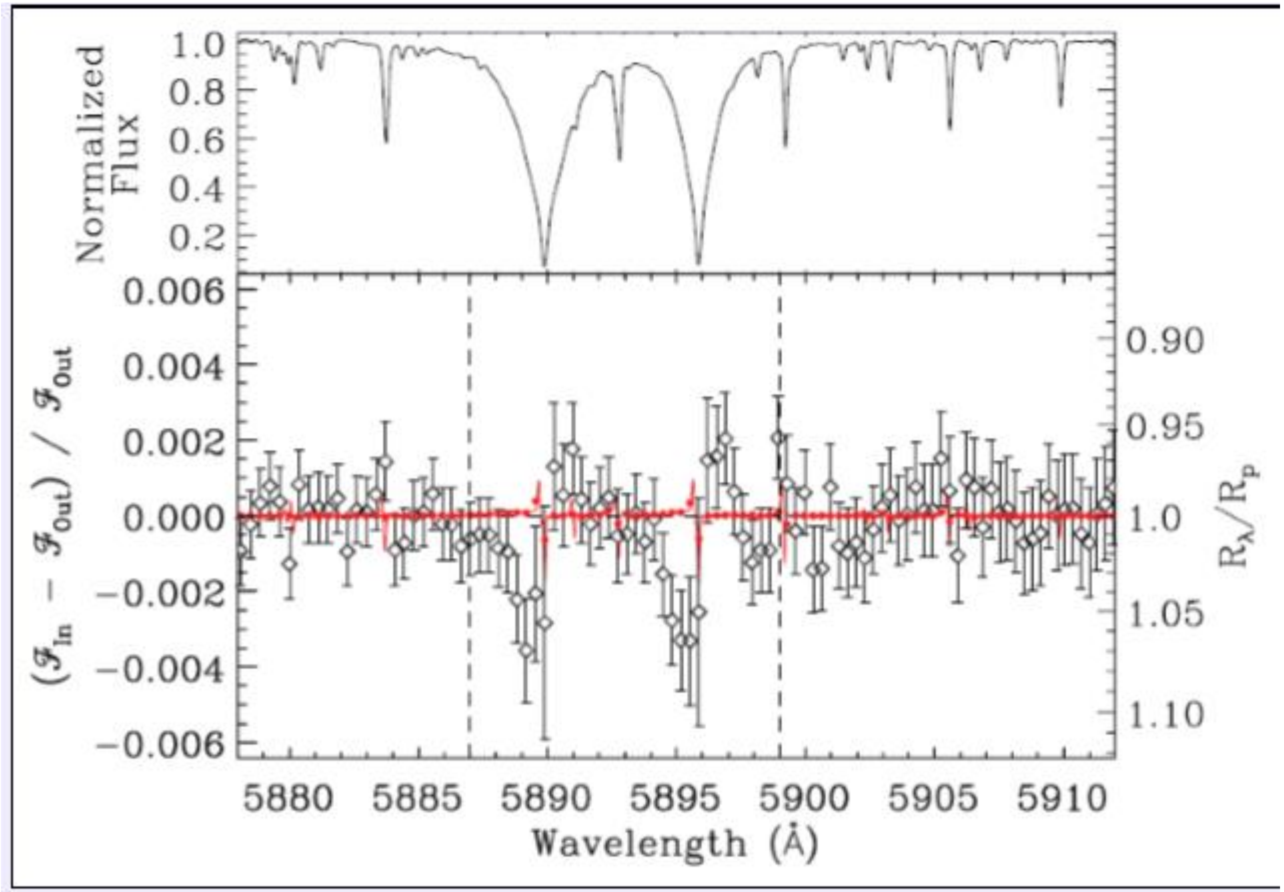


There are dark lines in the solar spectrum, which are result from the absorption by solar atmosphere (in this case, sodium)

Atmospheres of exoplanets: Transit method

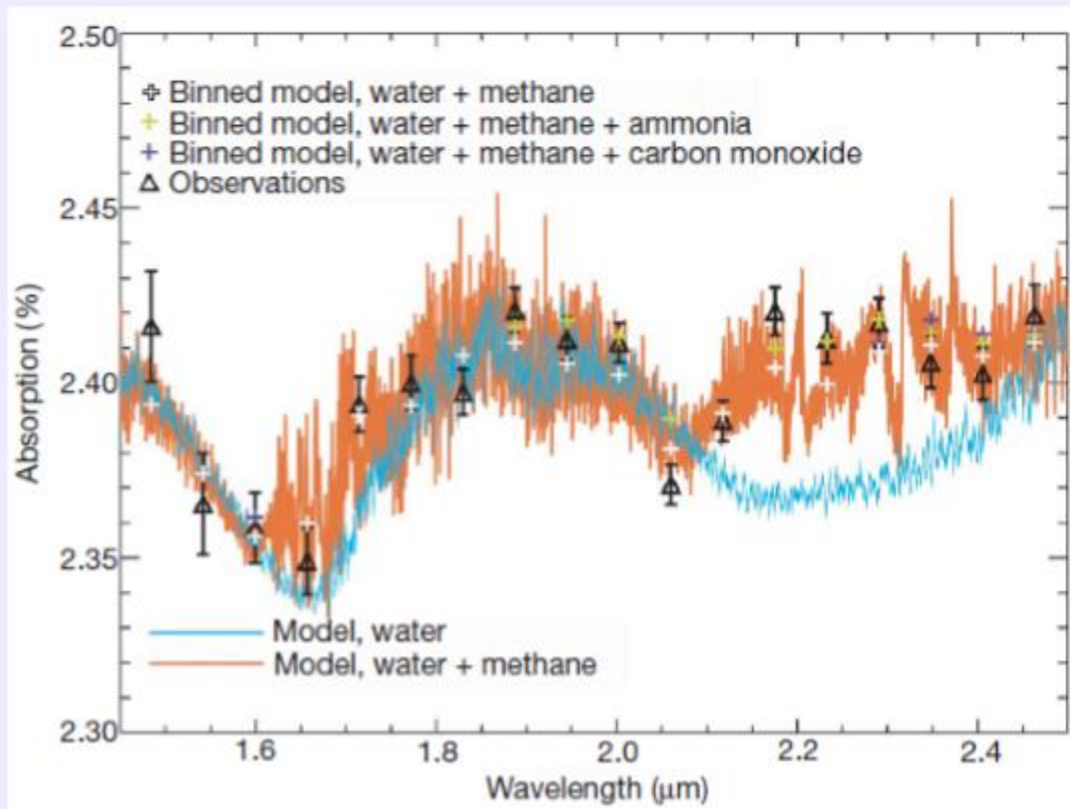


Sodium atmosphere (HD209458b, HD189733b)



Spectrum of HD189733b during the transit (Redfield et a;., 2008)

Vapor and CH_4



Observation by Hubble/NICMOS. Red line: CH_4+Vopor, blue: vapor only. Swain et al. (2008)

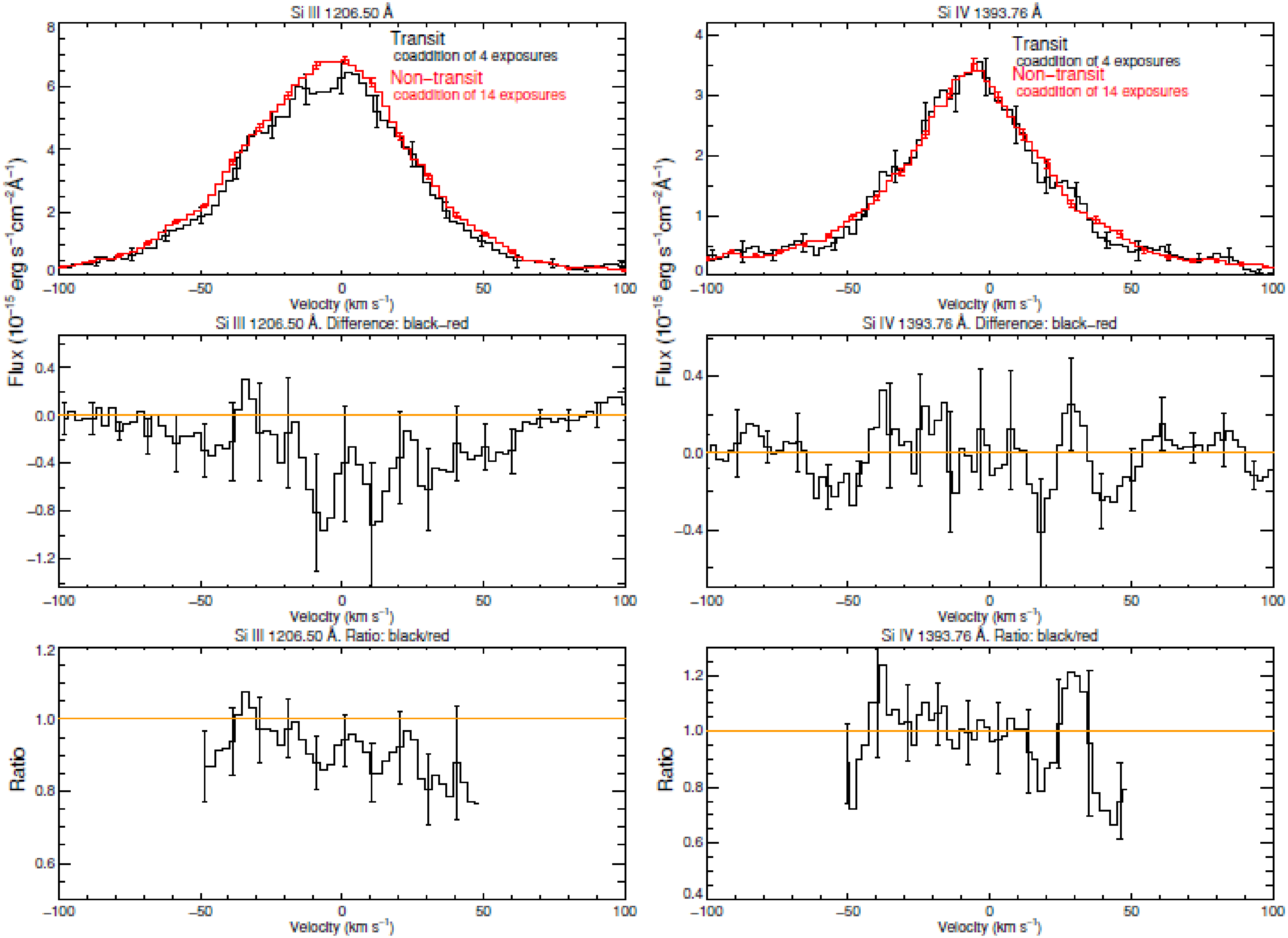


Figure 2. Upper panels: comparison of the four co-added spectra obtained during transit (black) with the co-added non-transit spectra (red) for the Si III and Si IV lines. Representative error bars per pixel are included. Middle panels: difference spectra (transit minus non-transit) with representative error bars. Lower panels: flux ratio (transit/non-transit) spectra. The ratios are not plotted beyond ±50 km s^{-1} as the errors are large at low flux levels. The velocity scale is relative to the −14.8 km s^{-1} radial velocity of the star.

(A color version of this figure is available in the online journal.)

Reference

- "Protostars and Planets V" Arizona University Press
- "Extrasolar Planets" Saas Fee Advanced Course 31
  Saas-Fee Advanced Courses
- "Planet Formation: Theory, Observations, and Experiments" Cambridge
- Reid & Hawley "New Light on Dark Stars" Springer

Satellites: General Introduction

Earth has one, Mars has two, Mercury and Venus do not have. On the other hand, Giant outer planets has many, for example, Jupiter has 69.

What is it?

How many does solar system have in total?

Satellites

Up to now, over 150 satellites have be found in the solar system.

Categorize:

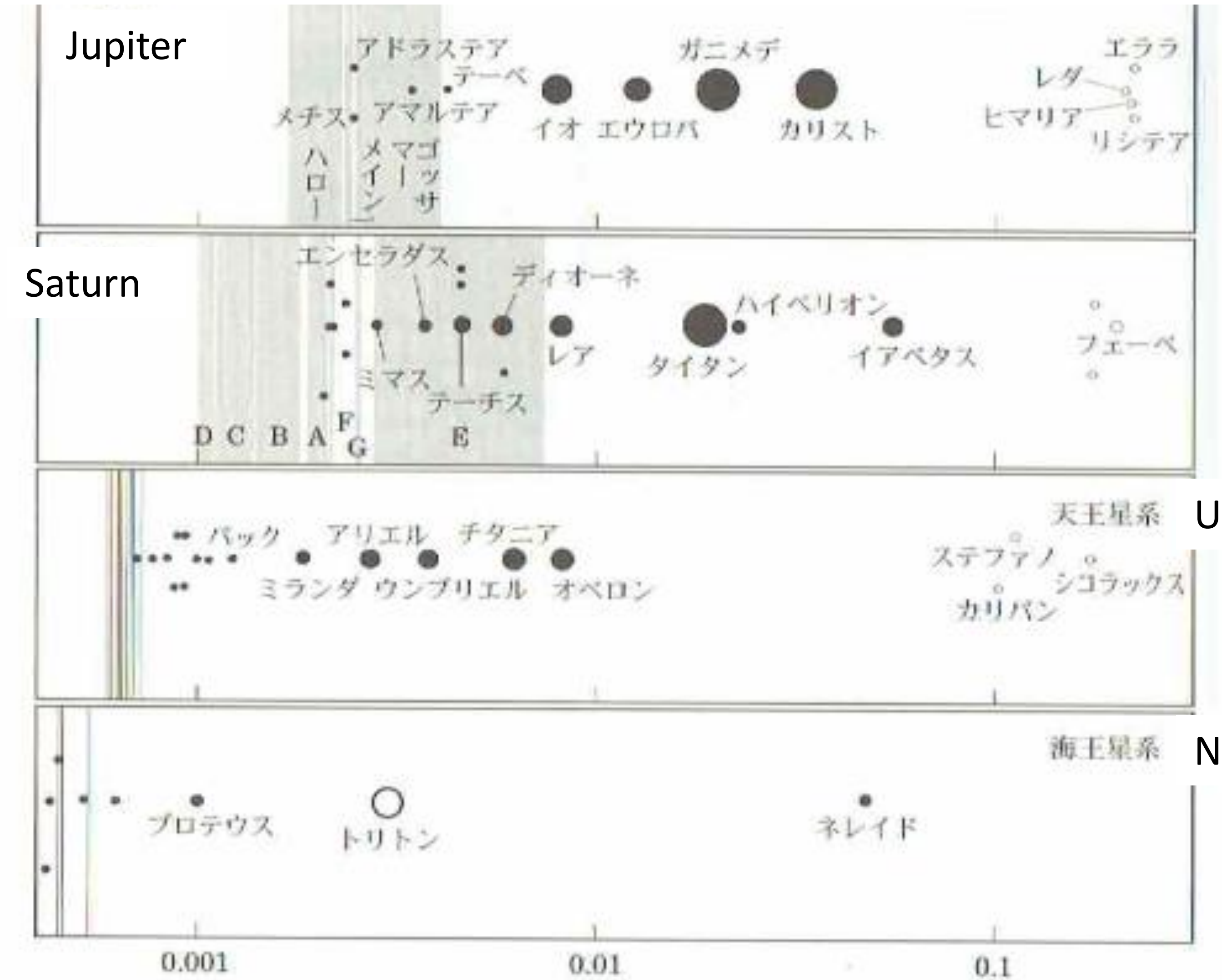
順行(Prograde motion): the same direction of planet spin.

-Regular satellites: nearly circular orbit on the equatorial plane of the planet
ex) 4 Major satellites of Jupiter, Io, Europa, Ganymede, and Callisto
-Irregular satellites: ex) Phobos (Mars).
Their origins might be Edgeworth-Kuiper Belt Objects.

逆行 (Retrograde motion)

-Regular satellites:
-Irregular satellites: ex) Triton (Neptune), small satellites of Jupiter.

Radius of orbit



Orbital radius normalized by the radius of planet's gravitational sphere

図 4.1 木星型惑星の主要な衛星の軌道半径．軌道半径は各惑星の重力圏半径で規格化した．大きい衛星については相対的な大きさを円の半径で示す．白丸は不規則衛星を表し，灰色の領域はリングの位置を表す

Size of symbol indicates the size of satellite. White: irregular satellites, Gray hatch: position of Rings

Density and radius of satellite

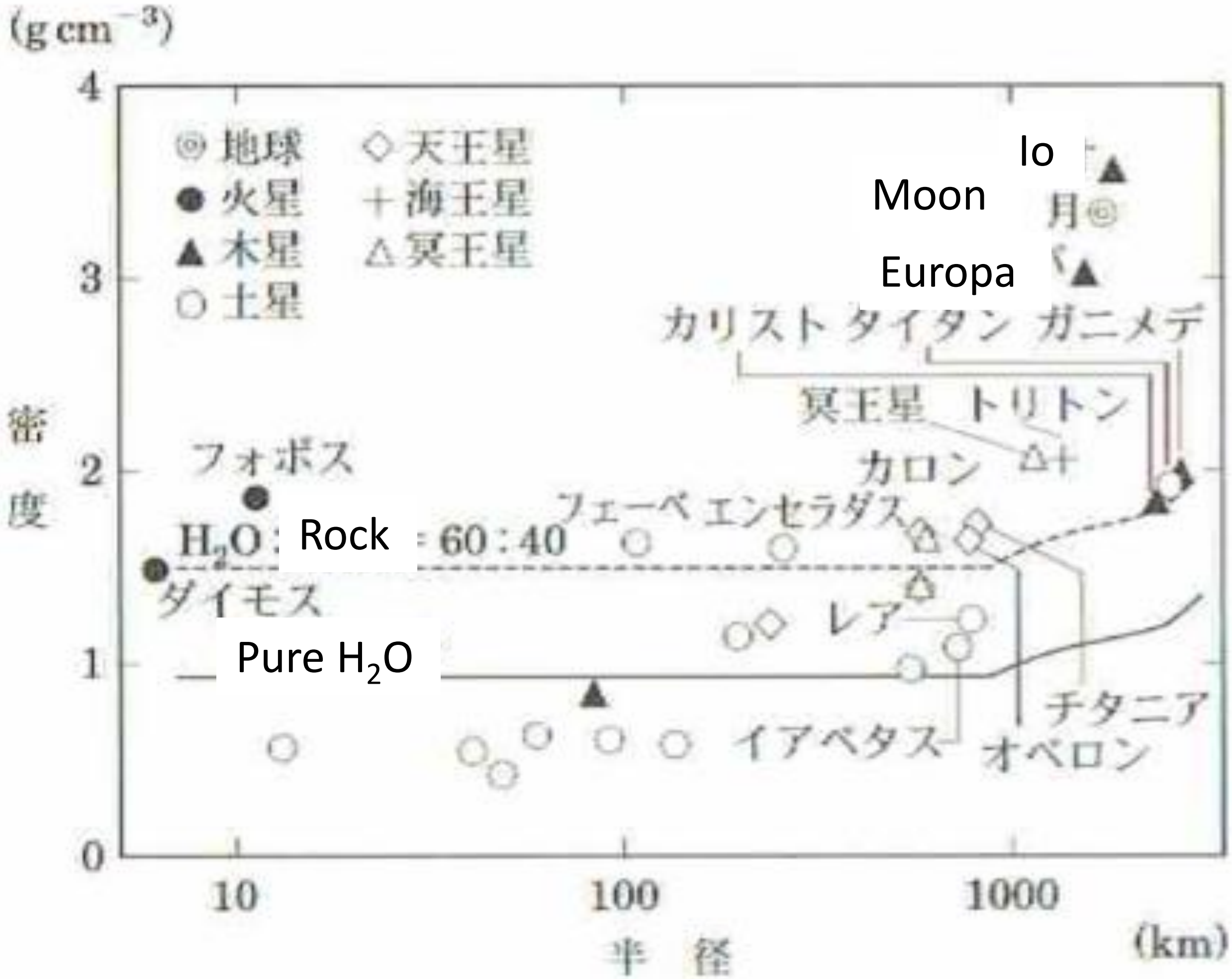


図 4.2　各惑星の衛星の密度と半径の関係（データは Jacobson *et al.* 2005, *BAAS*, 37 他による）. 冥王星については本体もプロットした. 実線と破線は純粋な H_2O 氷あるいは H_2O 氷と岩石成分が 60:40(質量比) で混合した場合の半径と質量の関係 (Lupo & Lewis 1979, *ICARUS*, 40) を示す.

Do they have the same origin and formation mechanism?

Maybe No!

Three major hypotheses of Satellites' formations

1. Formation from circumplanetary disk, sub nebula (周惑星星雲)

Analogous to a protoplanetary disk, it is very natural scenario.

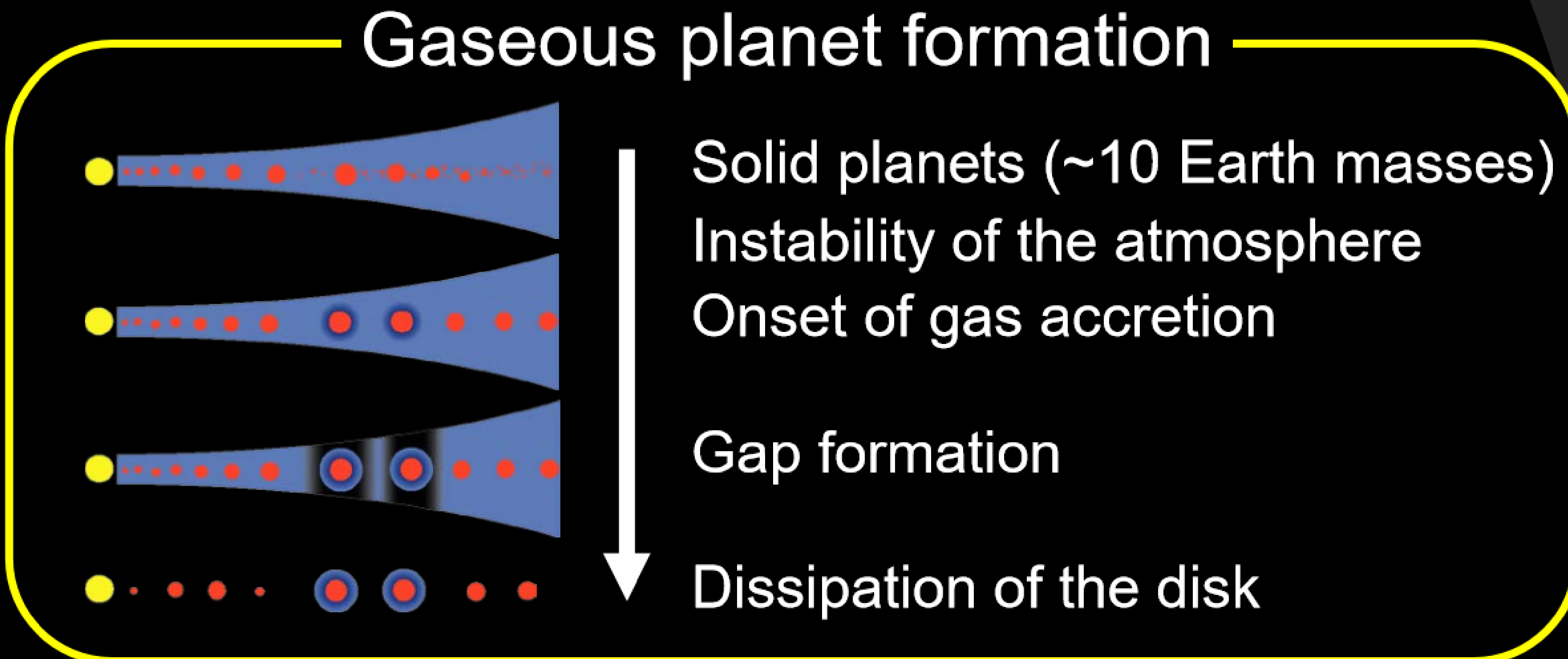
2. Captured body （捕獲説）

Small body was captured by gravitation of a large one (planet). An atmosphere around the large body (planet) acts as a brake to slow the movement of a passing object. Gravitational capture is the origin of Neptune's major moon Triton, the moons of Mars, and Saturn's moon

3. Giant impact (隕石衝突説)

(Ex) Moon formed out of the debris left over from a collision between Earth and an astronomical body, whose size is believed to be equivalent to Mars. This hypothesis is currently the favored scientific hypothesis for the formation of the Moon.

Formation of Gas-giants



Satellites are thought to be formed at very end of giant planet formation

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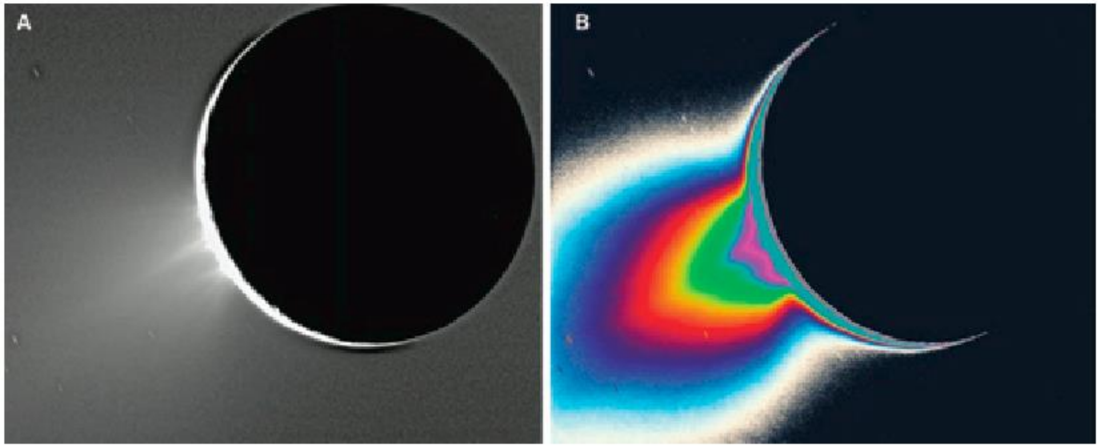
Please remember that hypothesis is just a hypothesis.

潮汐加熱 Tidal heating

There are currently volcanic activities on Earth, Io, Enceladus and **Triton** (Neptune).
Where do their energies come from?

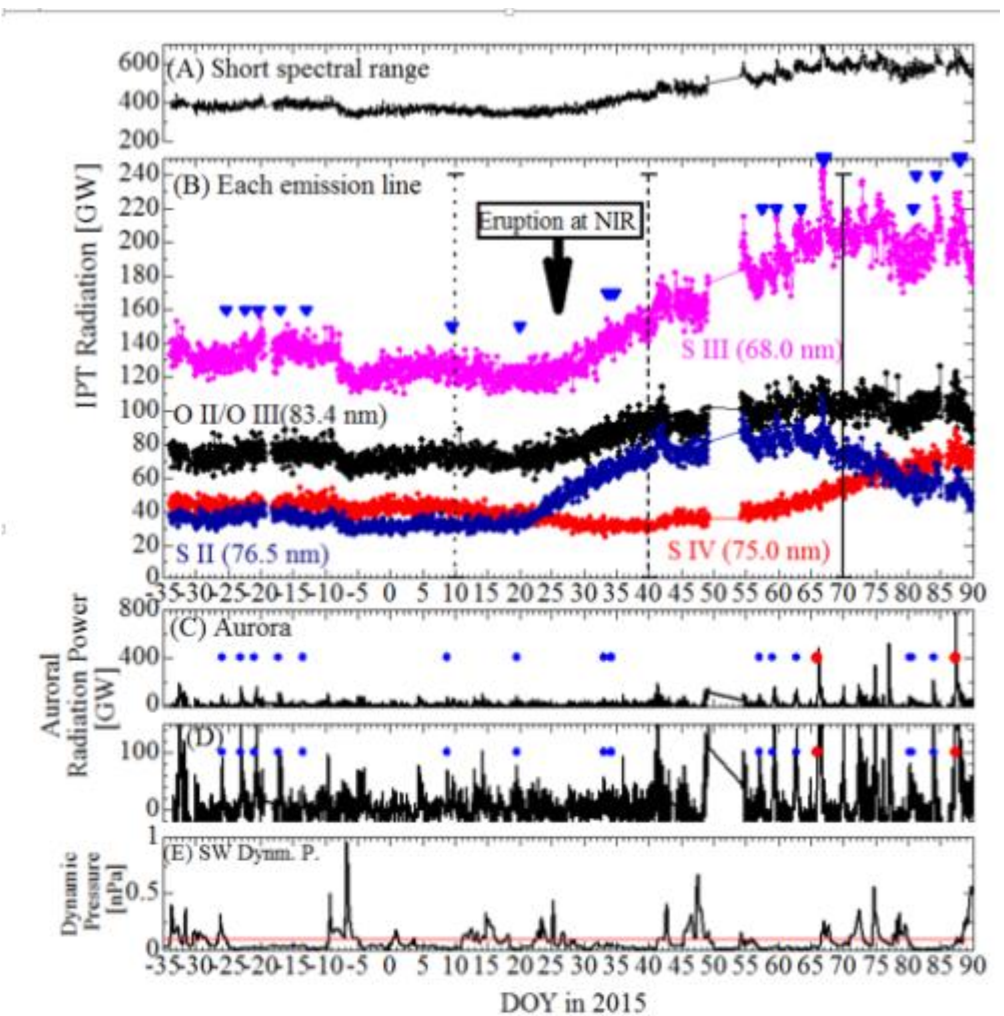
Enceladus

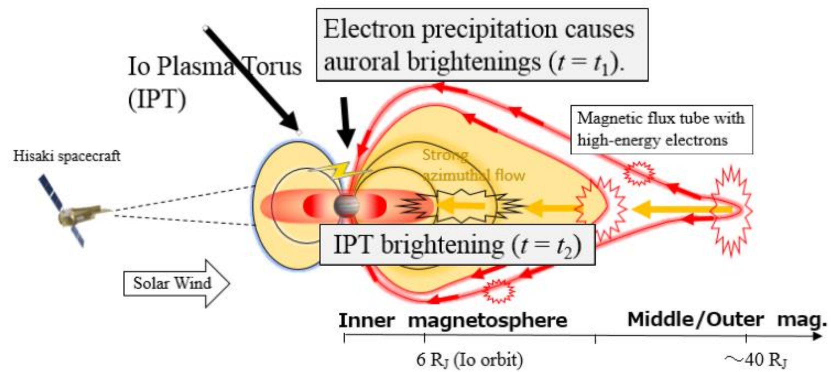


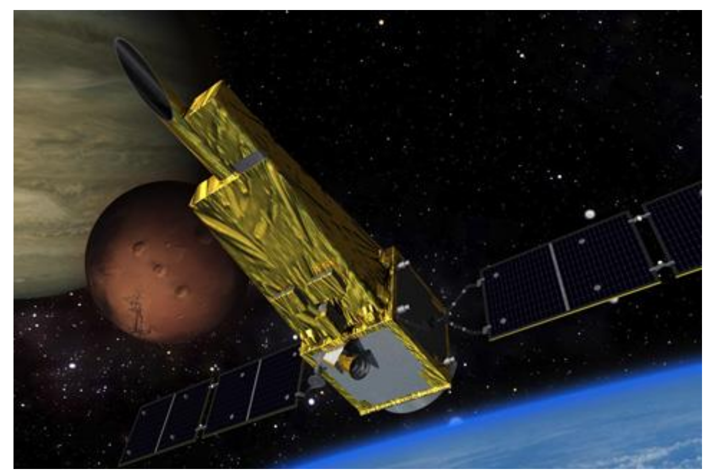
Io

Energies are coming from
- "Accretion Energy"
- Heat from radioactive elements, K, Th, and U.
  - cf. He(4) is created from U and Th, Ar (40) is from K.
- Tidal Heating (潮汐加熱)

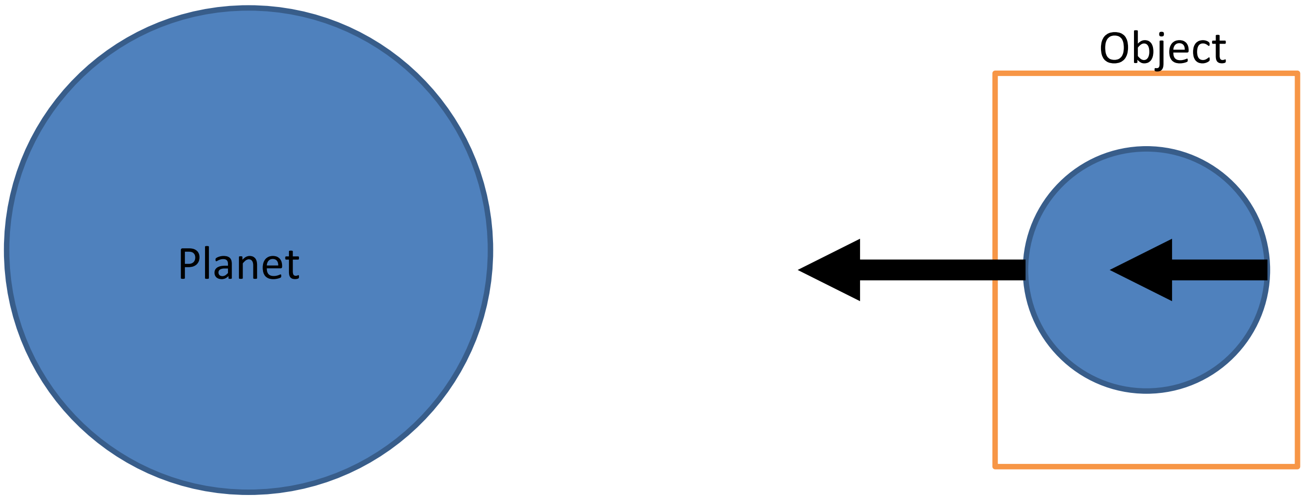
Volcanic activity on Io, observed by Japanese space telescope, Hisaki







潮汐加熱 tidal heating



When an object is in an elliptical orbit around the planet, the tidal force acting on is stronger near periapsis than by apoapsis. The deformation of the object due to tidal forces varies during its orbit, generating internal friction which heats its interior.