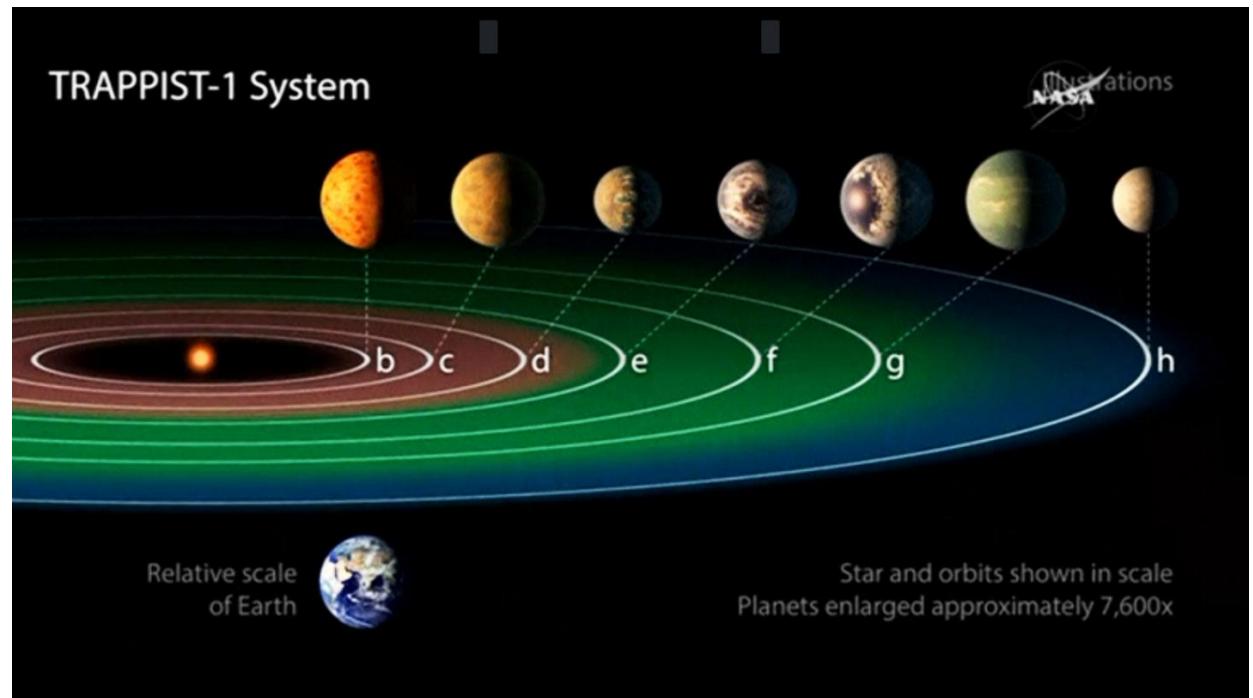


# AST 296LB

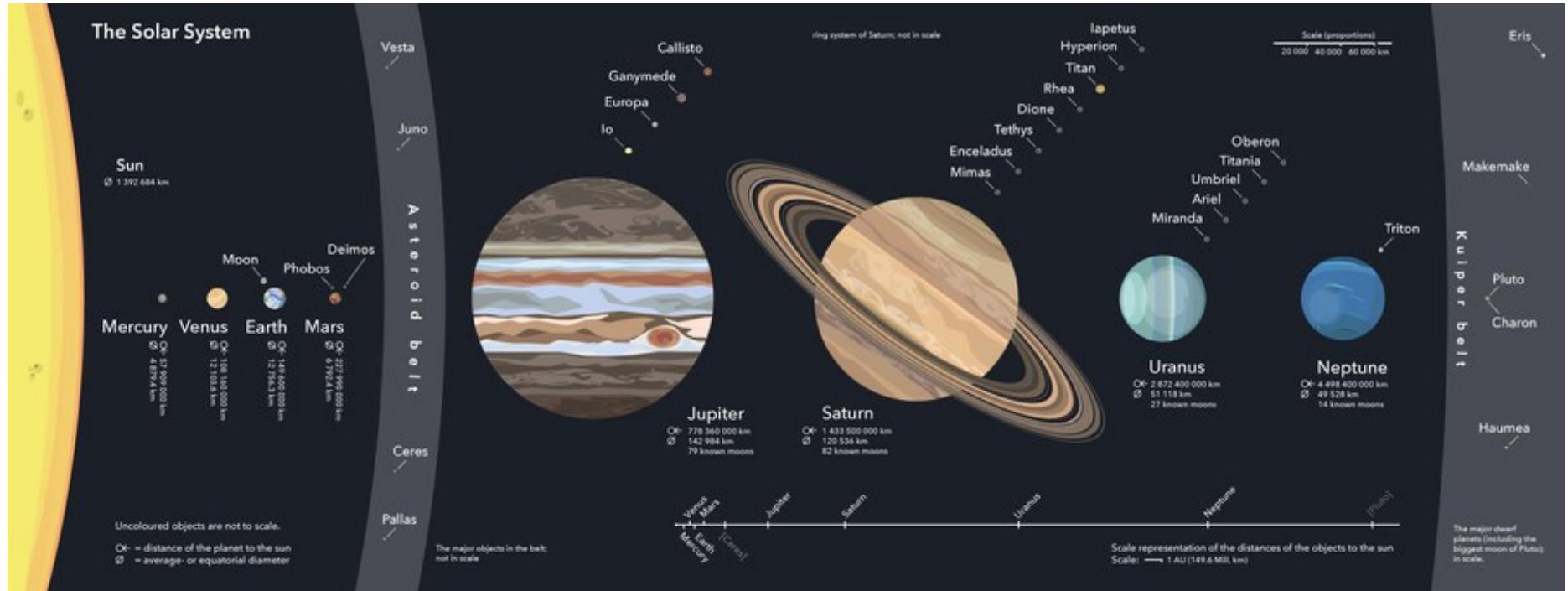
## Astronomy with Python

### Exoplanets! (Also, a little about the Solar System)



David Sand  
U of Arizona

# Our Solar System (in one or two slides)



## High level

- The Sun contains 99.8% of the mass in the solar system.
- Most remaining mass is confined to a flattened disk.
- All planets revolve in the same direction; most rotate in the same direction.
- All objects seem to have a similar age of 4.6 billion years.

# Two types of planets: Terrestrial and Jovian

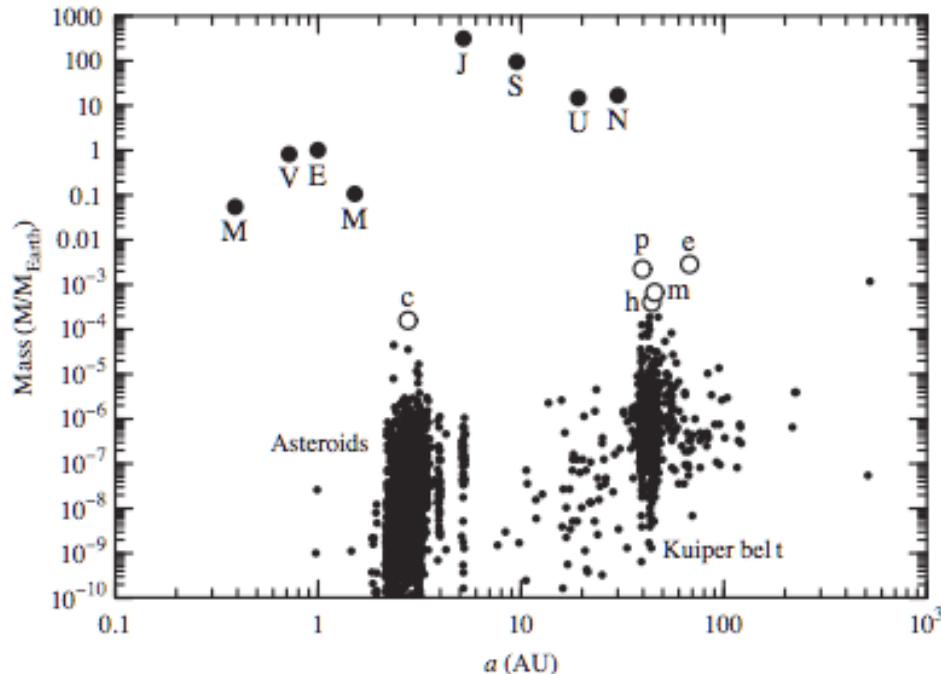
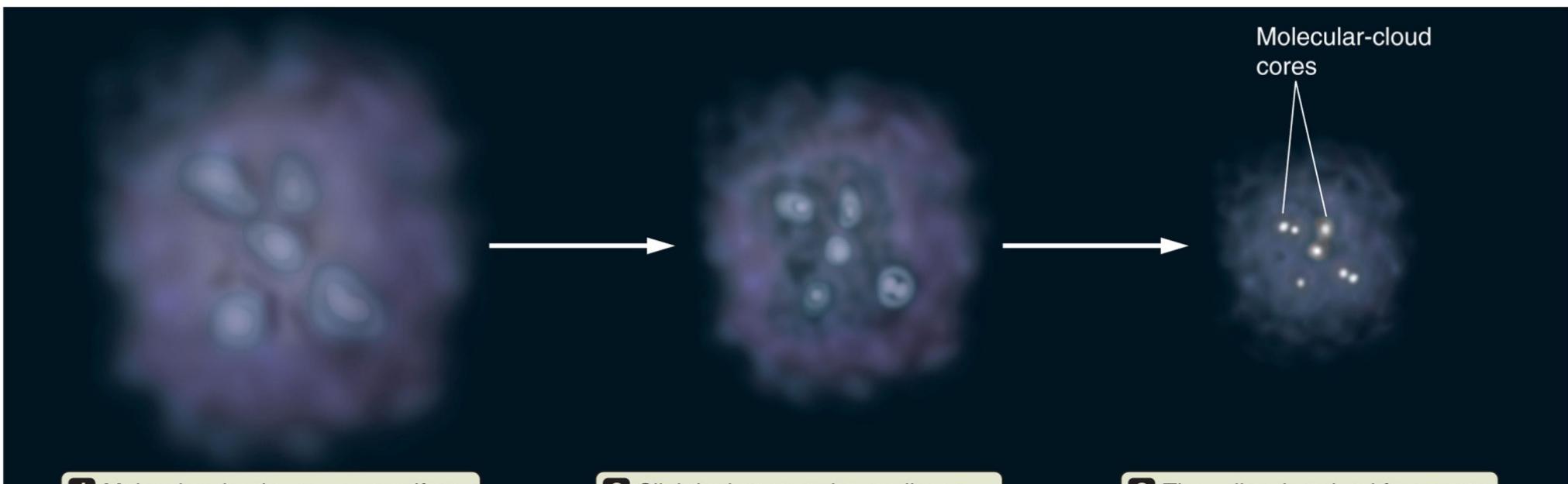


TABLE 8.1 Characteristics of Planetary Types

| Characteristic    | Terrestrial   | Jovian  |
|-------------------|---|---|
| Mass              | Low ( $\leq 1 M_{\oplus}$ )                                 | High ( $> 10 M_{\oplus}$ )                                |
| Composition       | Rocky/metallic<br>( $\rho \gtrsim 3000 \text{ kg m}^{-3}$ ) | Gaseous/icy<br>( $\rho \lesssim 2000 \text{ kg m}^{-3}$ ) |
| Rotation          | Slow ( $P \geq 24 \text{ hr}$ )                             | Fast ( $P < 18 \text{ hr}$ )                              |
| Satellites        | Few   | Many  |
| Distance from Sun | $a < 2 \text{ AU}$  | $a > 5 \text{ AU}$  |

What explains the difference?

# Star/Solar System formation

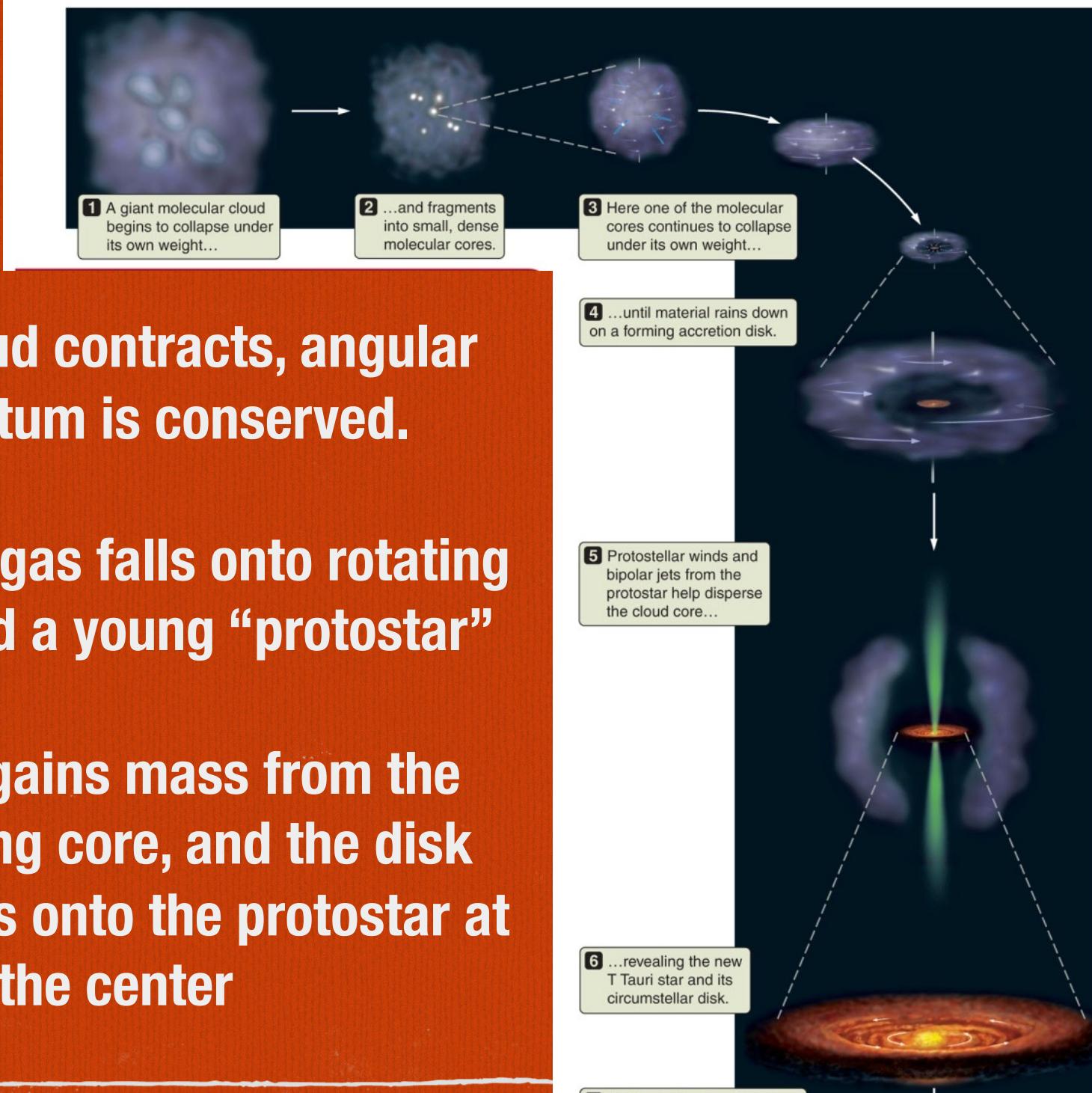


1 Molecular clouds are never uniform. Some regions inside the cloud are more dense than others.

2 Slightly denser regions collapse faster than their surroundings, and become more pronounced.

3 The collapsing cloud fragments into dense, star-forming cores.

# Core Collapse



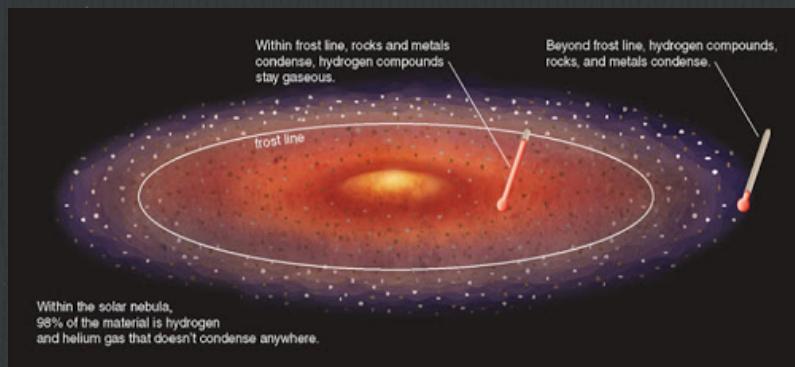
**As the cloud contracts, angular momentum is conserved.**

**Most of the gas falls onto rotating disk around a young “protostar”**

**The disk gains mass from the surrounding core, and the disk dumps mass onto the protostar at the center**

# Condensation

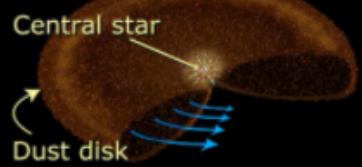
Gas disk from which planets form is hotter towards the center and cooler outside.



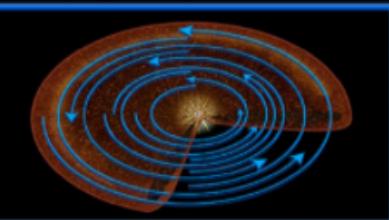
**TABLE 8.4** Simplified Condensation Sequence

| T (K) | Condensate         | Planet         |
|-------|--------------------|----------------|
| 1500  | Metal oxides       | Mercury        |
| 1300  | Fe, Ni             |                |
| 1200  | Silicates          |                |
| 700   | FeS (iron sulfide) | Venus          |
| 200   | H <sub>2</sub> O   | Earth, Mars    |
| 150   | NH <sub>3</sub>    | Jovian planets |
| 120   | CH <sub>4</sub>    | Pluto, Eris    |
| 65    | Ar, Ne             |                |

# Very Schematic



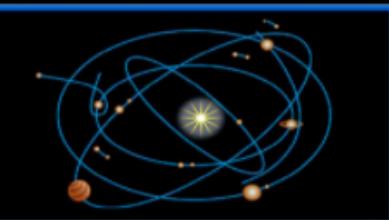
Orbiting dust grains accrete into "planetesimals" through nongravitational forces.



Planetesimals grow, moving in near-coplanar orbits, to form "planetary embryos."



Gas-giant planets accrete gas envelopes before disk gas disappears.



Gas-giant planets scatter or accrete remaining planetesimals and embryos.

## Accretion of solid condensates

### Planetesimals (~1+ km)

### Planetesimals drawn together gravitationally - 'coalescence'

### Metal-rich, rocky materials coalesce near Sun; Rocky+Icy far from Sun

### Outer planets, once >15 MEarth can retain H and He and groooowwww

# Arizona History

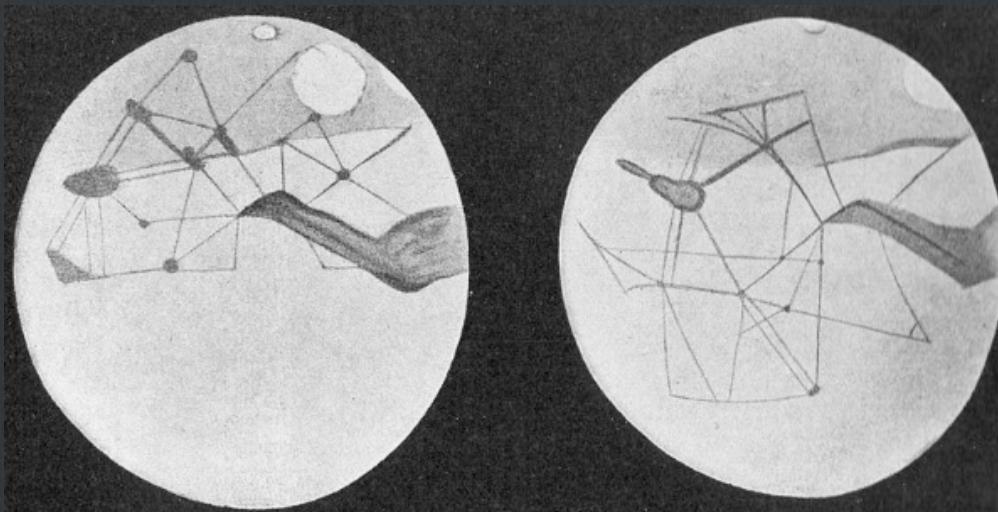
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Percival Lowell:  
Two famous ideas

1. The Martian surface is covered with canals. Not true

This was  
debunked  
by the first  
Martian  
Orbiter in  
1965



# Arizona History

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2. Planet X exists,  
pulling on Neptune  
like Neptune pulls  
on Uranus. True!  
sort of

The original Clark Telescope in  
Flagstaff, AZ



# Arizona History

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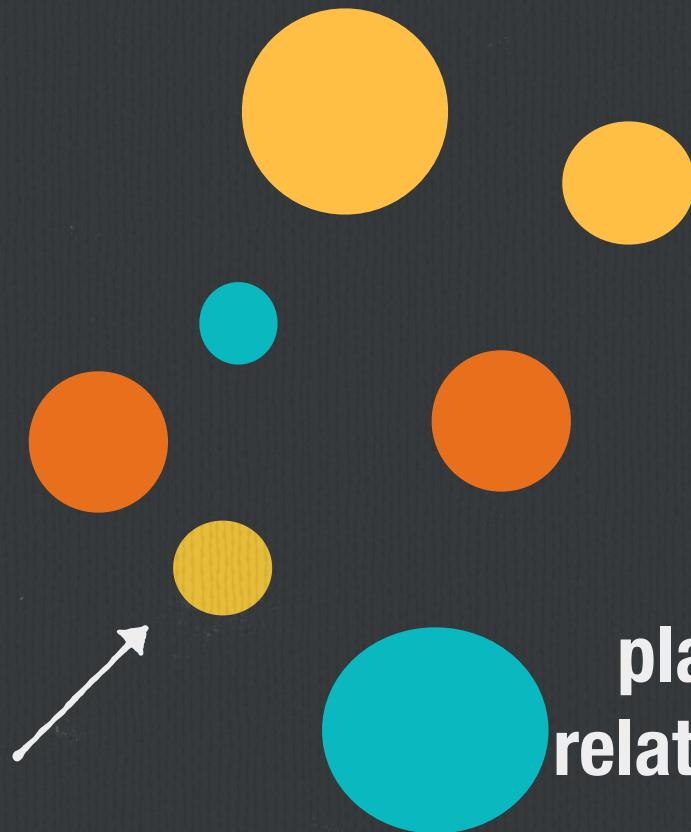


**Lowell never found Pluto, but he left money in his will for someone to continue the search: Clyde Tombaugh was hired (w/o a degree) to scan the sky for another planet**

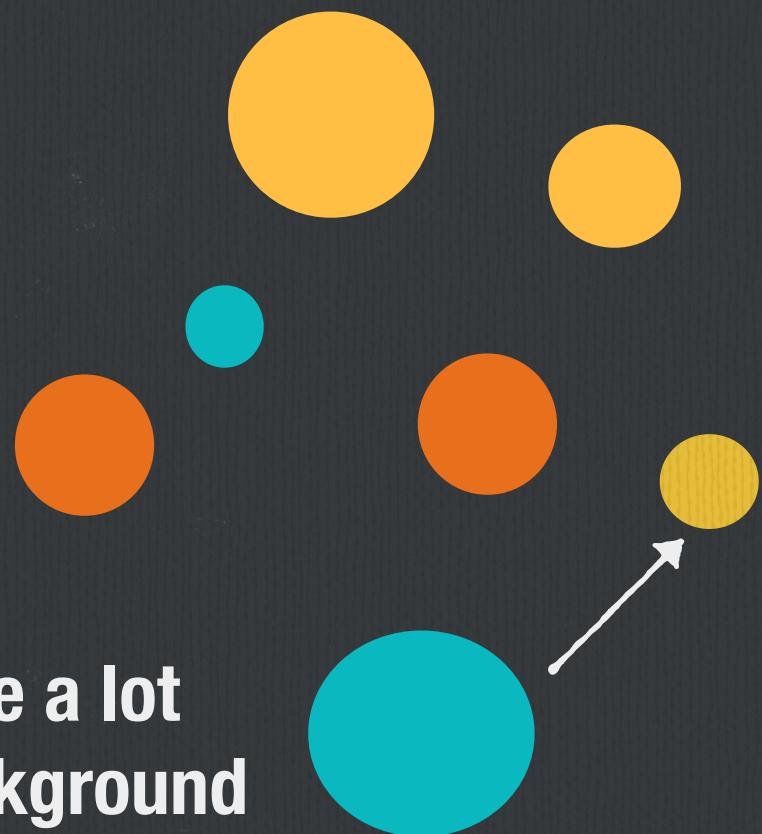
**How? Taking images night after night, looking for something that moved relative to the other stars**

# Finding planets (and asteroids)

Picture 1



Picture 2



planets move a lot  
relative to background  
stars

# The discovery of Pluto: Arizona History

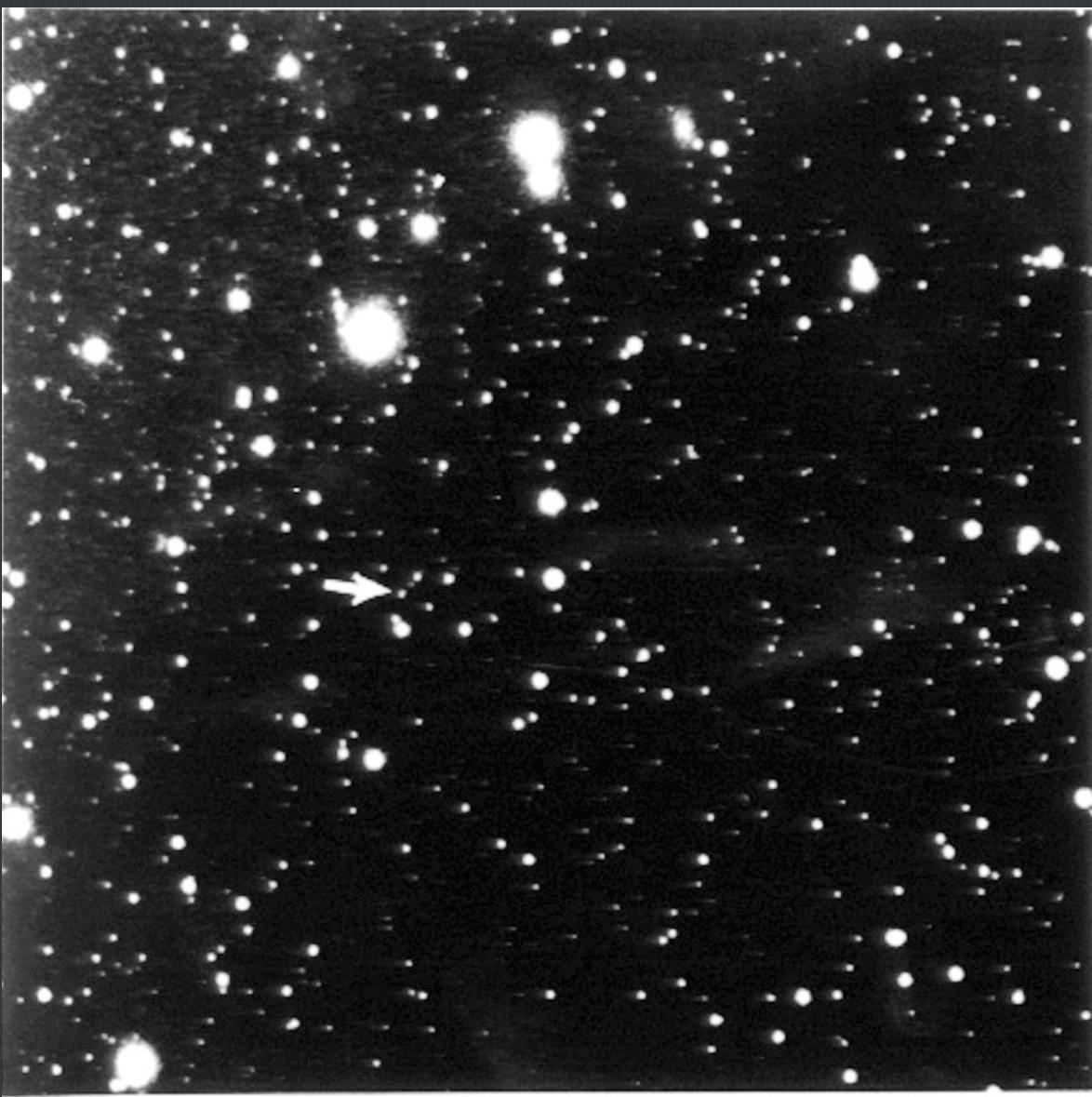
DISCOVERY OF THE PLANET PLUTO



January 23, 1930



January 29, 1930



# Planet Detection Methods

- Mercury-Saturn (Babylonians?)



- Uranus (Herschel) **1781**



- Neptune (Adams, Galle, Le Verrier\*) **1840s**

- Minor Planets (Tombaugh, Brown, et al)



$$\begin{aligned} & B \int_{x_0}^{x_m} \frac{ctgx - 2}{2\pi x^3} dx \quad \epsilon = 2,79 \quad A - C = \\ & x \rightarrow 1 \quad \sum_{n=0}^{+\infty} \frac{x^n}{n!} \quad f = \sqrt{\frac{\sum (x-m)^2}{n+1}} \quad S = \int_{t=2}^{\infty} f(t) dt \quad C \\ & + y^2 = 2 \quad e = \cos x + t \sin x \quad 5^{\circ} \text{ and } \alpha \quad j = \frac{\alpha x}{4\pi} \\ & P = r^2 \pi \quad h/x = \frac{(y-x)}{x} \quad \Delta x = \frac{h}{r} \quad \Delta y = \frac{\Delta x + 2}{r-1} \\ & \Delta t = T - \frac{3\pi}{x} \quad \Delta x = \frac{h}{r} \quad \Delta y = \frac{\Delta x + 2}{r-1} \\ & (x-y)^2 = 2^2 + 3x^2 \quad (y-x)^2 = x^2 + 2ax + a^2 \quad f_k = \\ & y = 2^2 + 3x \quad (y-x)^2 = \left(\frac{y}{2}\right)^2 \quad X_{k/2} = \frac{b \pm (a-c)}{\sqrt{2a}} \\ & \int \frac{dx}{x} \quad \sum_{i=0}^{\infty} x_i^a \quad \pi \approx 3,1415 \quad \tan(2\alpha) = \frac{2\tan(\alpha)}{1-\tan^2(\alpha)} \\ & P = \sum_{i=0}^{\infty} x_i^a \quad j = \frac{\alpha x}{4\pi} \quad h = \sqrt{a^2 - b^2} \quad S_s = \begin{bmatrix} 100 \\ 101 \\ 101 \\ 100 \end{bmatrix} \\ & = (y-1)^2 \quad \sin \alpha = \frac{b}{h} \end{aligned}$$

# **Exoplanet Detection Techniques**

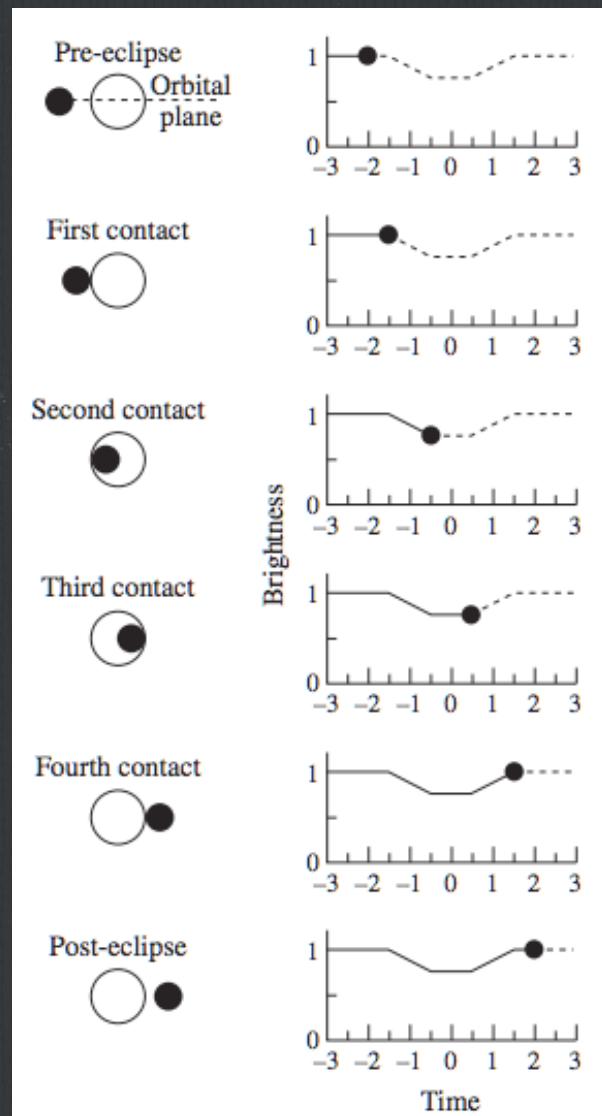
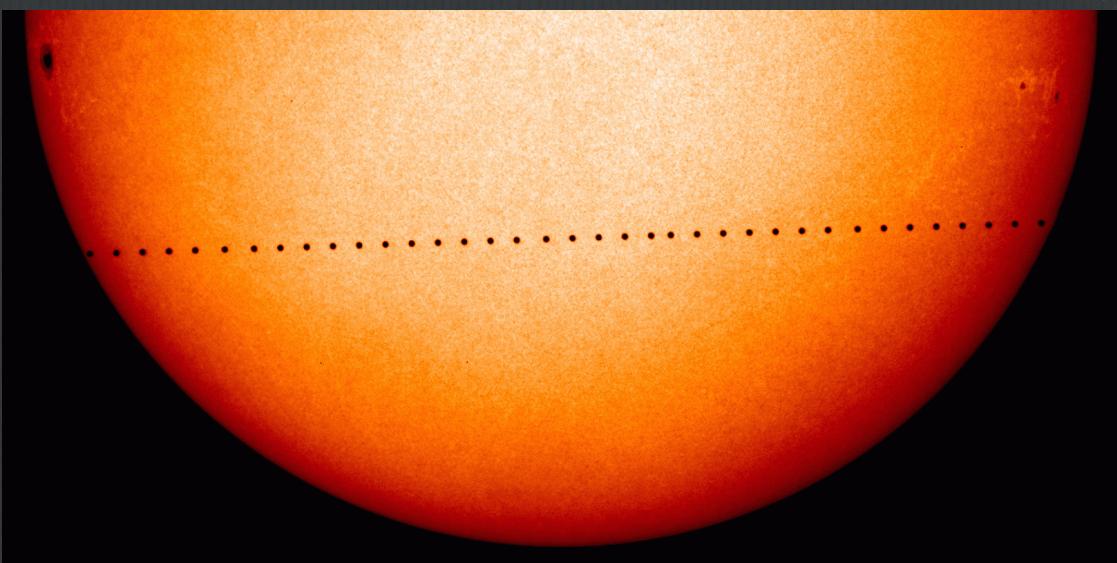
- **Direct Detection** — Kind of obvious, but very difficult.
- **Radial velocity Technique** — Use the doppler shift to measure slight ‘wobbles’ in a star’s motion.
- **Transit** — Literally see a mini-eclipse as the planet passes between us and the star.

## Transit Method

[https://www.cfa.harvard.edu/~avanderb/tutorial/  
tutorial.html](https://www.cfa.harvard.edu/~avanderb/tutorial/tutorial.html)

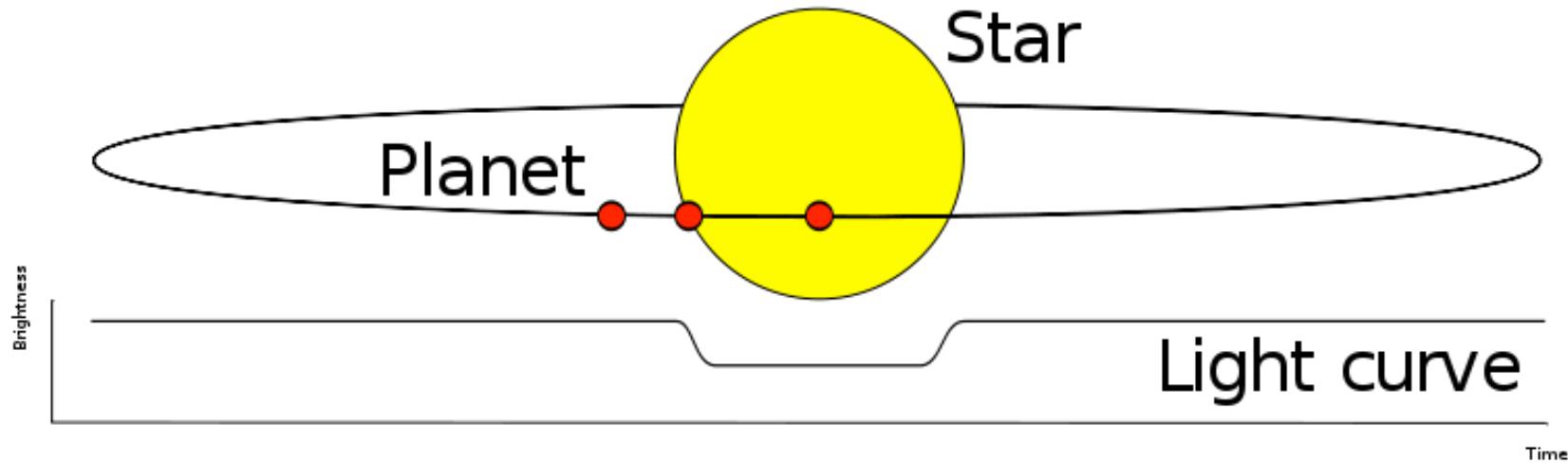
**Witnessing the passage of a planet between its parent star and the observer.**

**Unlike observing a transit in the Solar System, neither the star nor the exoplanet can be resolved from Earth. But the exoplanet can be detected indirectly.**



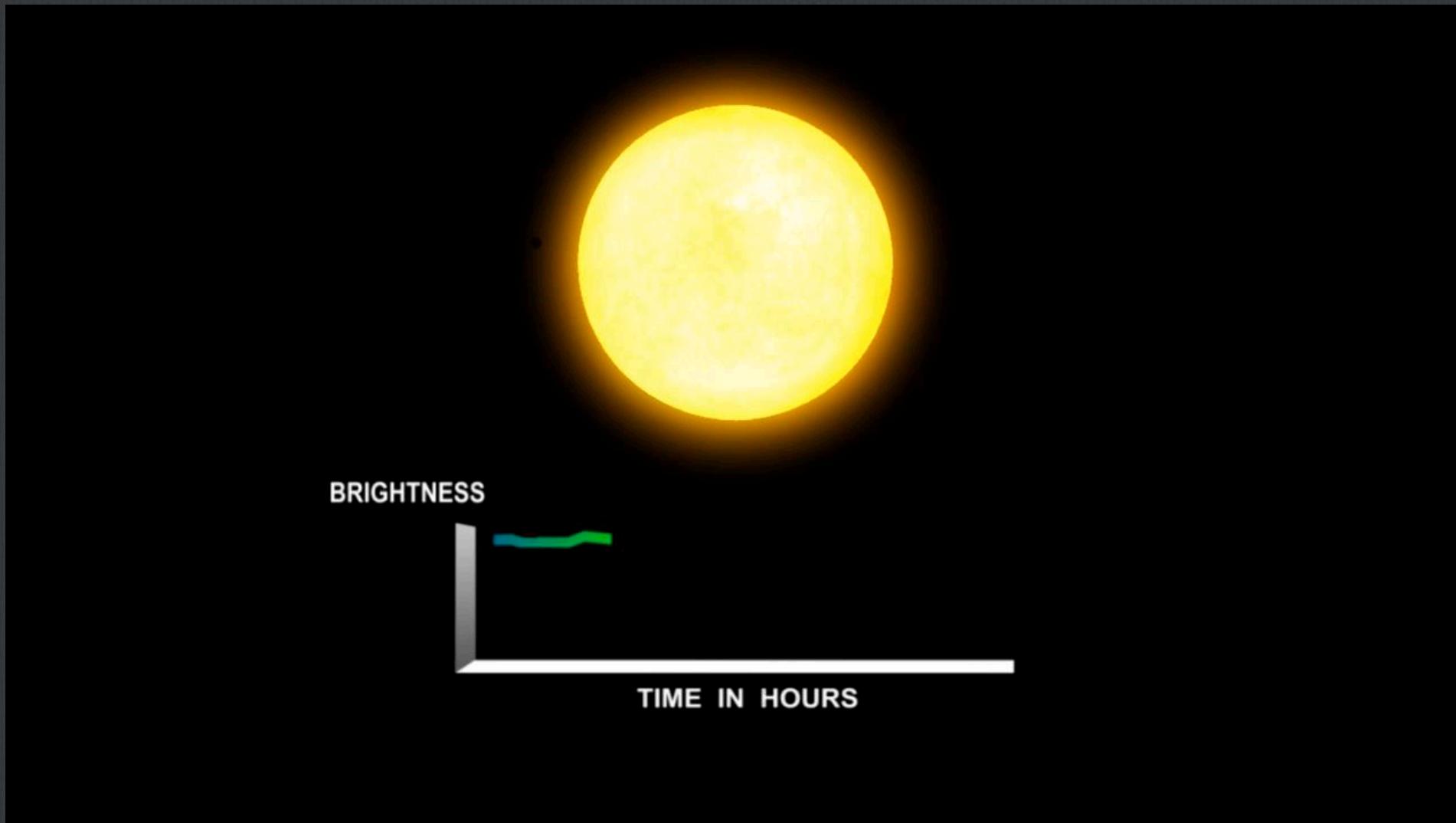
## EXOPLANET DETECTION: TRANSITS

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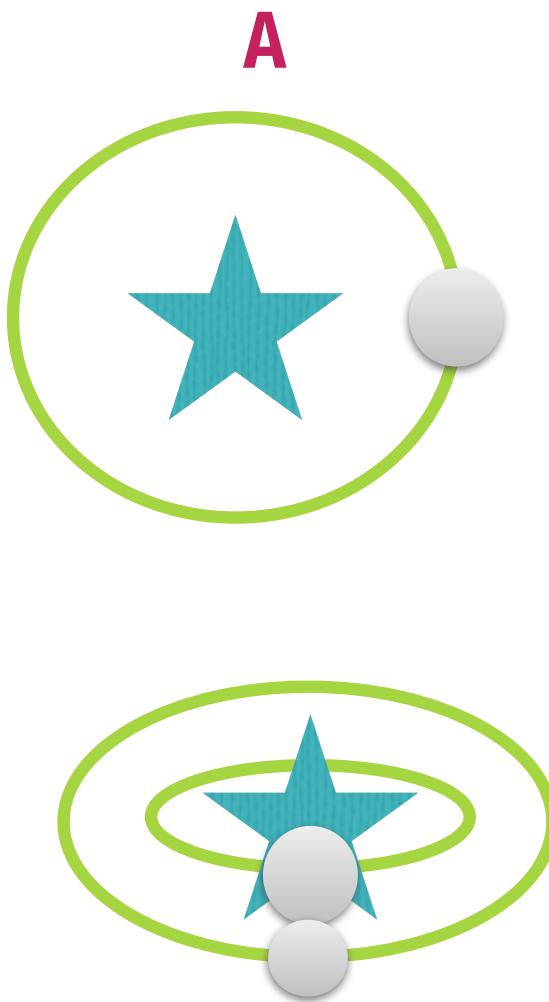


**THIS \*ONLY\* WORKS WHEN THE PLANET AND STAR ARE  
LINED UP WITH OUR LINE OF SIGHT**

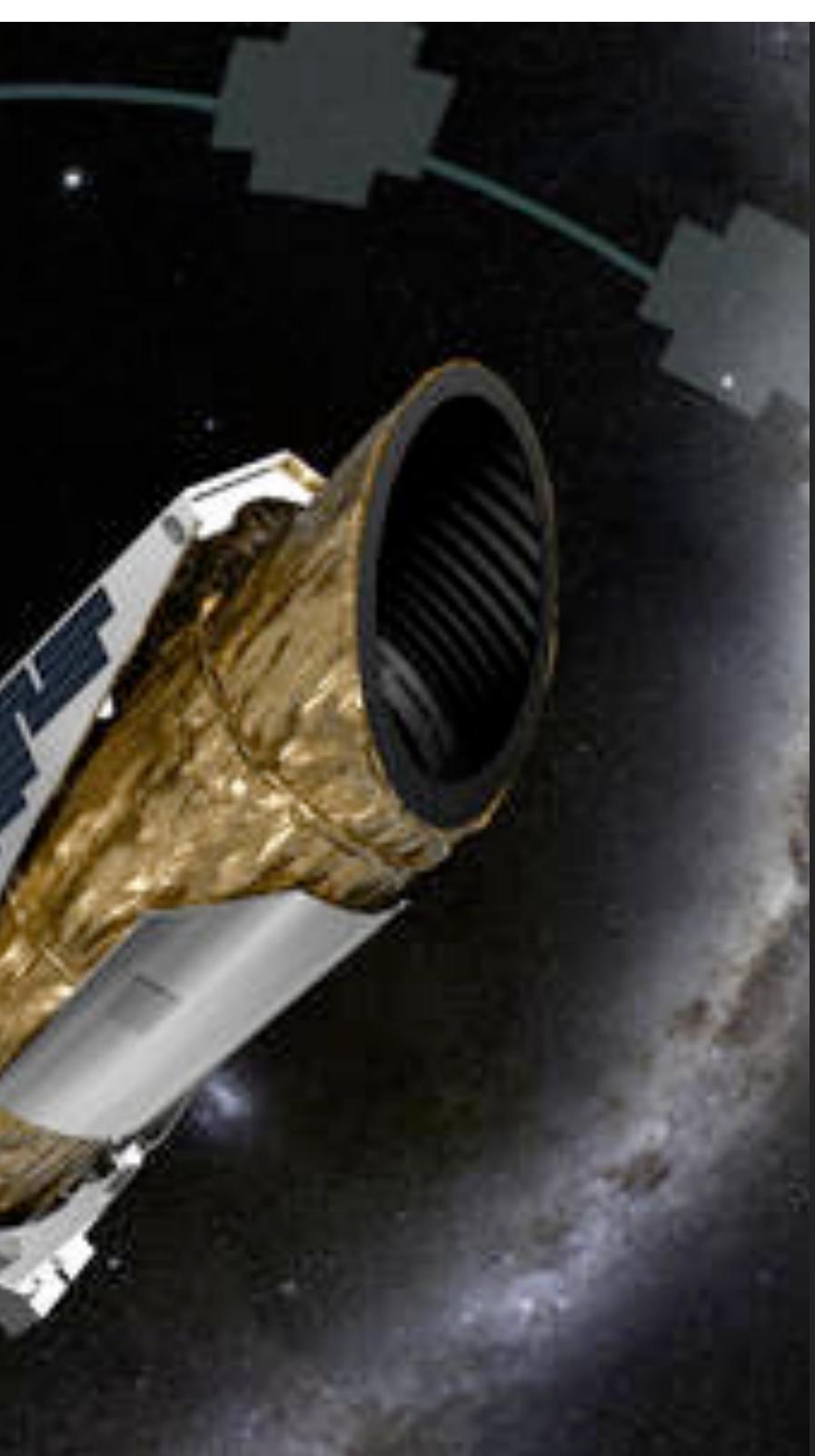
# Exoplanet Detection: Transits



## WHAT KIND OF PLANETS ARE EASIER TO SEE TRANSIT?



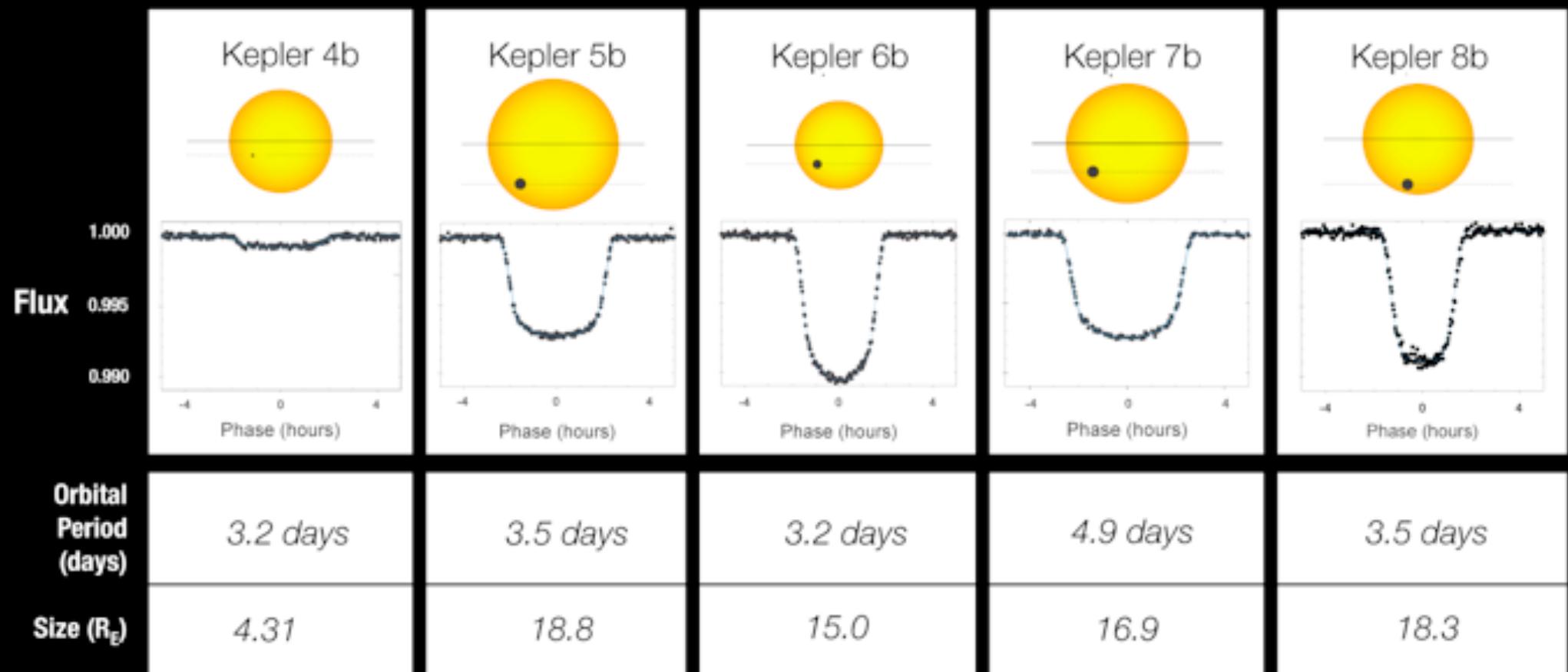
IF A PLANET REALLY CLOSE TO THE STAR IS A LITTLE BIT INCLINED TO OUR LINE OF SIGHT, WE CAN STILL SEE IT. BUT IF IT IS FAR AWAY FROM ITS STAR, IT WON'T TRANSIT



DESPITE SPECIAL ALIGNMENT, MOST PLANETS TO DATE WERE FOUND BY KEPLER. FOR 4 YEARS, IT STARED AT ONE TINY PATCH OF SKY AND WATCHED CHANGES IN THE BRIGHTNESS OF 100,000 STARS

# KEPLER SPACE TELESCOPE

# Transit Light Curves



Borucki et al 2010

# Kepler Orrery

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**1815 planets in 726 systems**

[https://www.youtube.com/watch?v=Td\\_YeAdygIE&action=share](https://www.youtube.com/watch?v=Td_YeAdygIE&action=share)

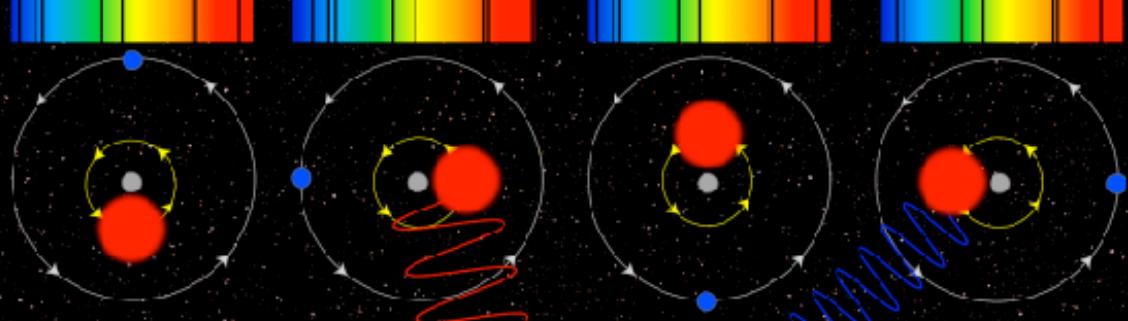
# EXOPLANET DETECTION METHODS: RADIAL VELOCITY

## Radial Velocity Method

The star and planet orbit their common center of mass.

Spectral lines move towards the red as the star travels away from us.

Spectral lines move towards the blue as the star travels towards us.



As the star moves away from us,  
light waves leaving the star are  
"stretched" and move towards the  
red end of the spectrum.

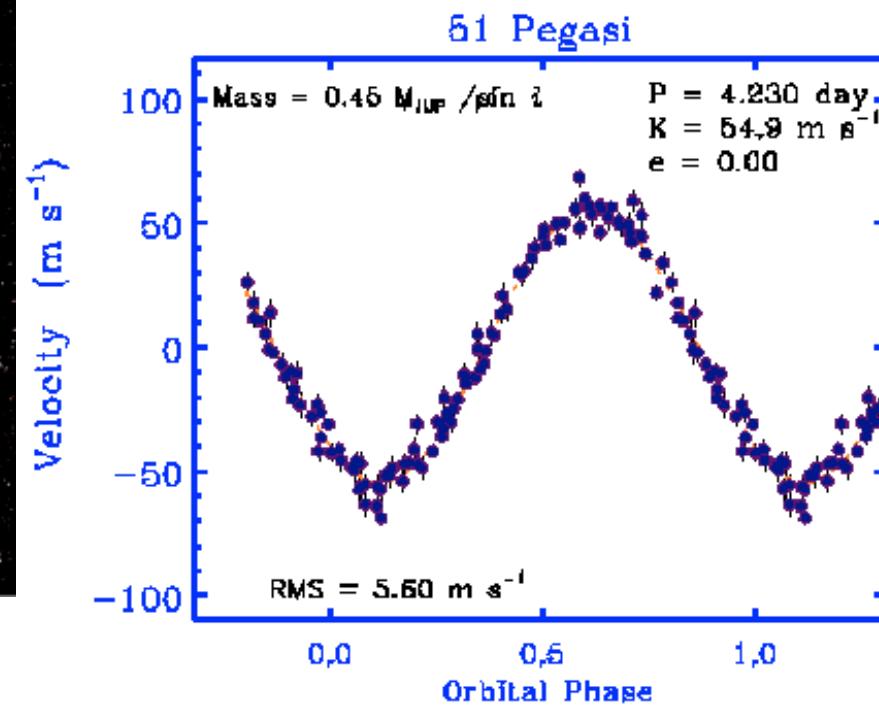
As the star moves towards us,  
light waves leaving the star are  
"compressed" and move towards the  
blue end of the spectrum.



Not to scale

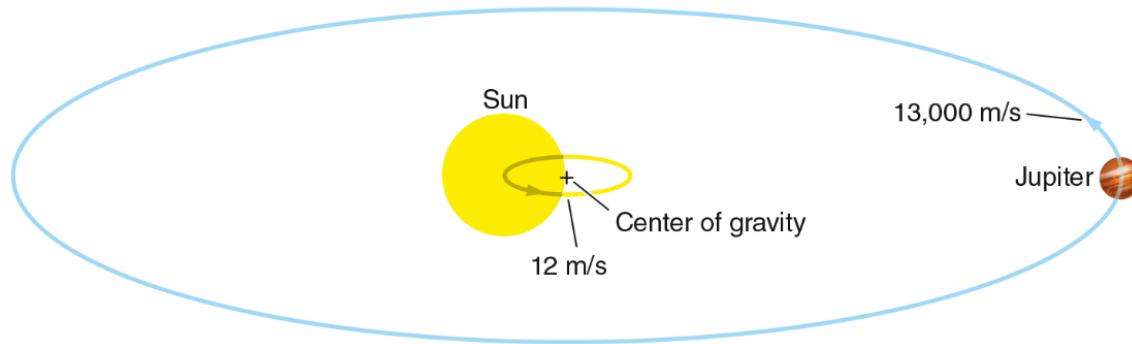


BY MEASURING THE  
VELOCITIES OVER TIME, WE  
CAN GET AN INDICATION OF  
THE MASS AND THE ORBITAL  
PERIOD.



# Could aliens like us detect planets in our solar system?

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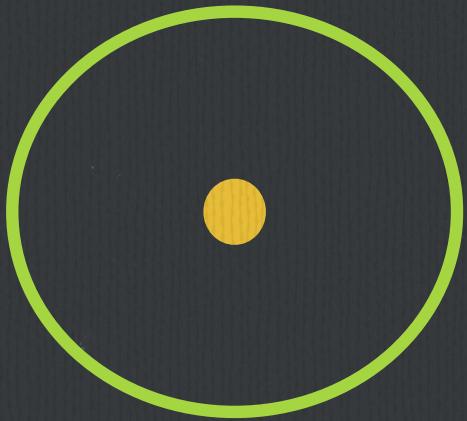
Current precision of radial velocity measurements,  
~1 m/s

Saturn induces a radial velocity of 2.7 m/s  
Earth induces a radial velocity of 0.09 m/s

# Which system will have the largest measured velocity change?

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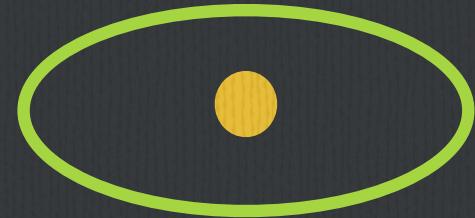
Face on  
A



Edge on  
B



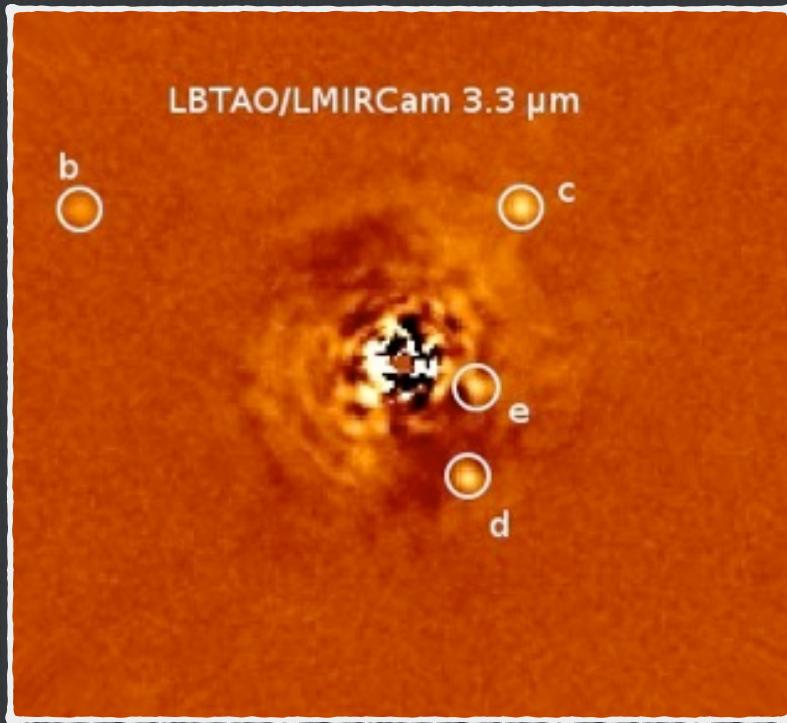
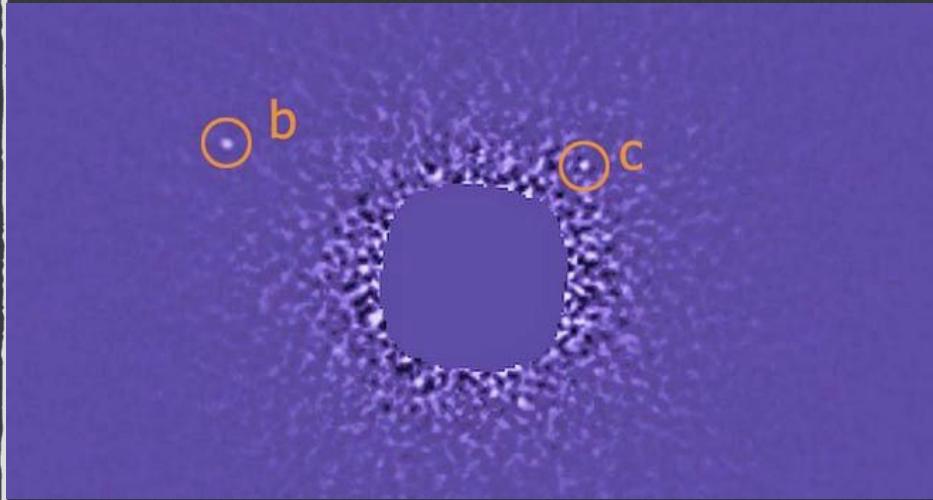
In the middle  
C



All the same system, but how will their MEASURED radial velocities change?

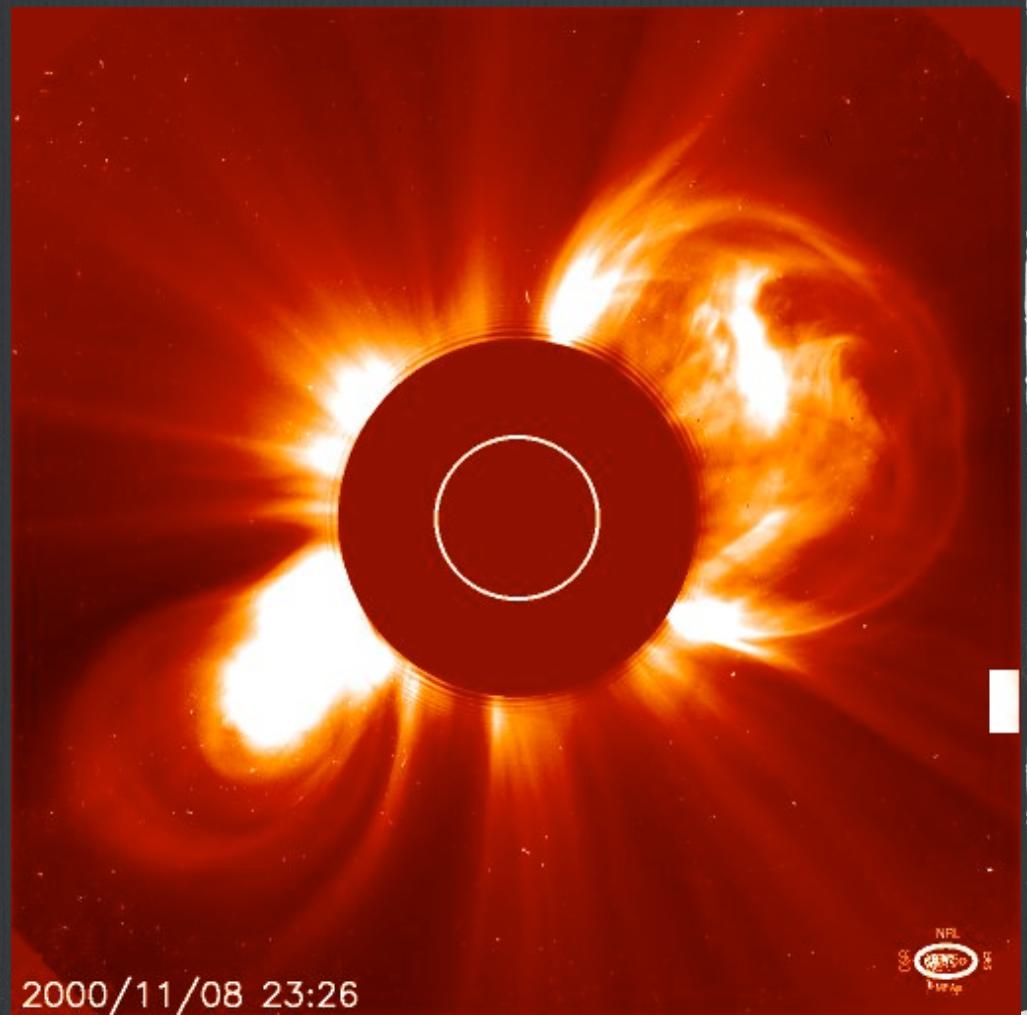
We can only know  $\text{mass} \times \sin(i)$  where  $i$  is the inclination

# Exoplanet Detection, the simplest way yet: take a picture!



uses a “coronagraph”

Hint: the name comes from ...



2000/11/08 23:26

# Selection Effects: What kinds of planets can we see?

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**Radial Velocity:**

more massive planet (or smaller star),  
close to the star

**Transits:**

bigger planets (or smaller stars),  
close to the star

**Imaging:**

brighter planets, far way from the star

# The Diversity of Exoplanetary Systems

