[24] Exoplanet Discovery (11/28/17)

Upcoming Items

1. Hope you had a great Thanksgiving!
2. Homework #11 due on Thursday.
3. Homework #12 due on Thursday, Dec 7
4. Read Ch. 13.3–13.4 by next class.

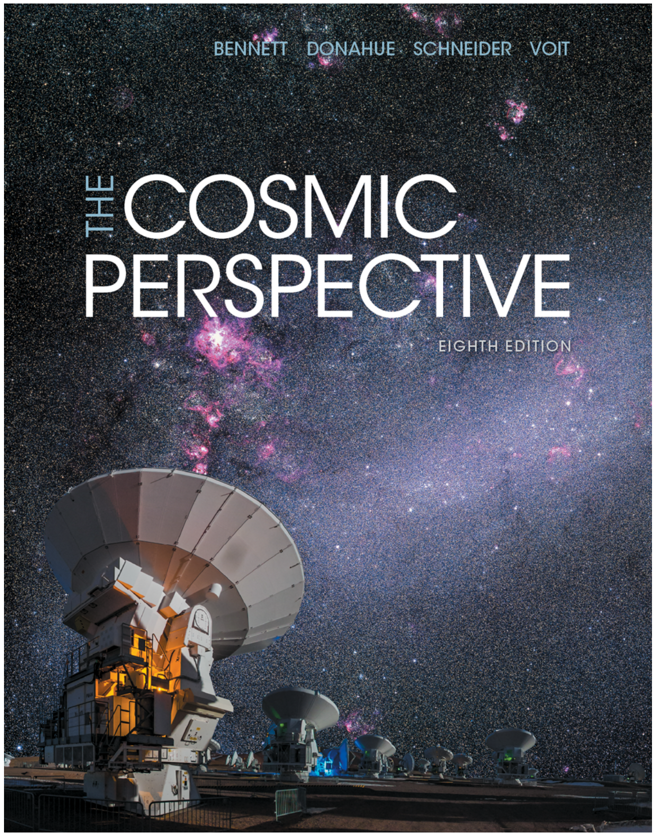
APOD 12/1/16

LEARNING GOALS

Ch. 5.4, 13.1–13.2

By the end of this lecture, you should be able to…

- … *use the Doppler effect to deduce the relative radial speed of a distant object;*
- … *describe current methods for detecting planets around other stars, and give advantages and disadvantages of each;*
- … *interpret a star's radial velocity graph to determine the semimajor axis and minimum mass of an unseen planet;*
- … *use transit data to infer the radius of a planet and combine this with radial velocity data to infer the planet density.*



Astronomy Colloquium Tomorrow

- This room (ATL 2400), 4:05-5 PM Wednesday
- Marshall Perrin of STScI:
  "Direct Imaging of Planetary Systems: Progress and Prospects”
- He will also talk about direct imaging of debris disks

- Physics colloquium today, in PHYS 1412:
  Nobel Laureate Joe Taylor (Princeton)
  “From Einstein’s Theory to Gravity’s Chirp”

Any astro questions?

In-Class Quiz

1. Which of the following techniques, if any, can provide the density of an exoplanet?

A. Radial velocities alone.
B. Transits alone.
C. Radial velocities plus astrometry.
D. Transits plus radial velocities.
E. None of these.

2. Suppose you found a star with the same mass as the Sun moving back and forth with a period of 16 months. What could you conclude?

A. It has a planet orbiting with a semimajor axis less than 1 AU.
B. It has a planet orbiting with a semimajor axis greater than 1 AU.
C. It has a planet orbiting with a semimajor axis of exactly 1 AU.
D. It has a planet, but we do not have enough information to know its orbital distance.

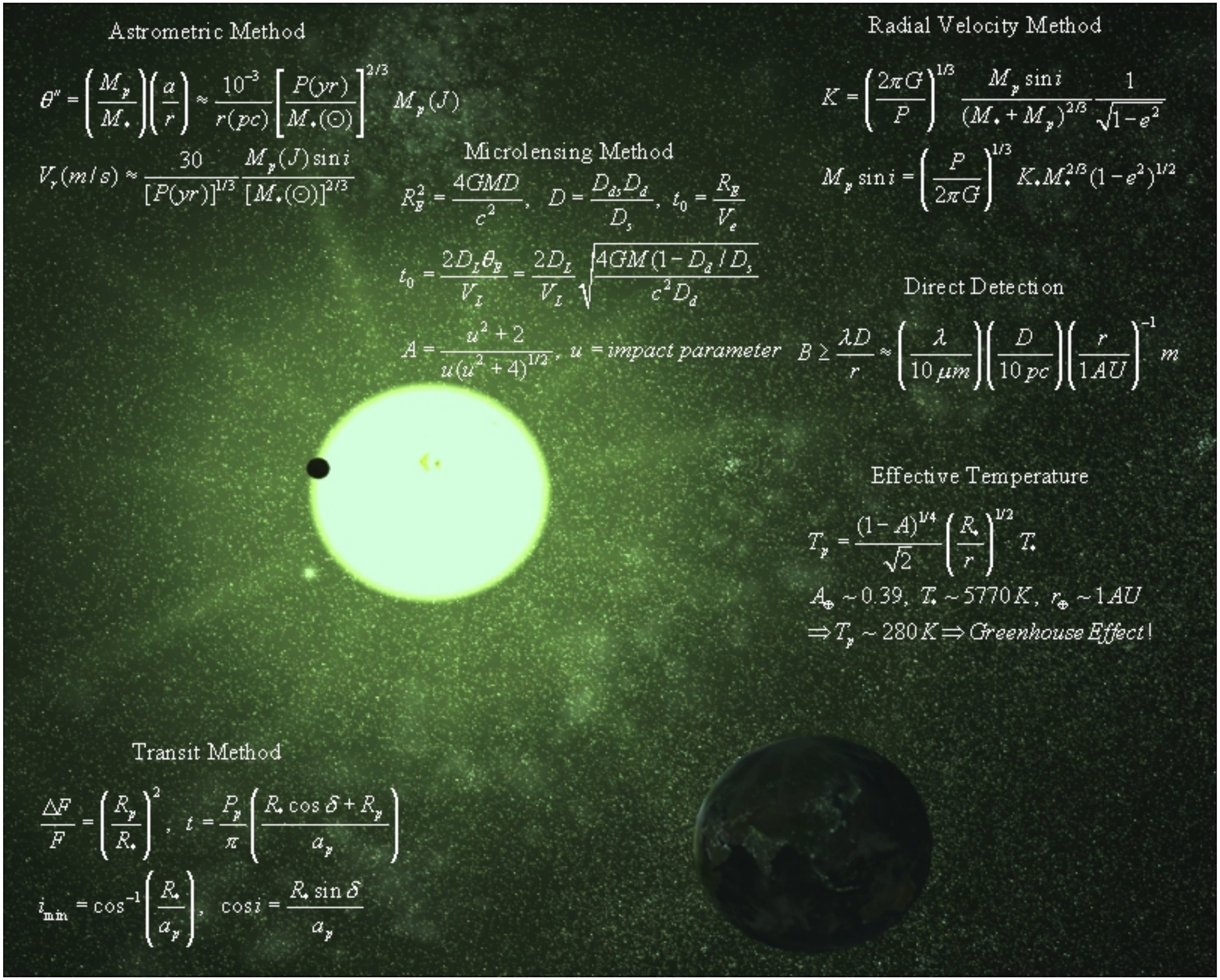
In-Class Quiz

1. Which of the following techniques, if any, can provide the density of an exoplanet?

A. Radial velocities alone.
B. Transits alone.
C. Radial velocities plus astrometry.
D. Transits plus radial velocities.
E. None of these.

2. Suppose you found a star with the same mass as the Sun moving back and forth with a period of 16 months. What could you conclude?

A. It has a planet orbiting with a semimajor axis less than 1 AU.
B. It has a planet orbiting with a semimajor axis greater than 1 AU.
C. It has a planet orbiting with a semimajor axis of exactly 1 AU.
D. It has a planet, but we do not have enough information to know its orbital distance.



Astrometric Method

$$\theta'' = \left(\frac{M_p}{M_\star}\right)\left(\frac{a}{r}\right) \approx \frac{10^{-3}}{r(pc)}\left[\frac{P(yr)}{M_\star(\odot)}\right]^{2/3} M_p(J)$$

$$V_r(m/s) \approx \frac{30}{[P(yr)]^{1/3}}\frac{M_p(J)\sin i}{[M_\star(\odot)]^{2/3}}$$

Microlensing Method

$$R_E^2 = \frac{4GMD}{c^2},\quad D = \frac{D_{ds}D_d}{D_s},\quad t_0 = \frac{R_E}{V_e}$$

$$t_0 = \frac{2D_L\theta_E}{V_L} = \frac{2D_L}{V_L}\sqrt{\frac{4GM(1-D_d/D_s}{c^2 D_d}}$$

$$A = \frac{u^2+2}{u(u^2+4)^{1/2}},\ u = impact\ parameter$$

Radial Velocity Method

$$K = \left(\frac{2\pi G}{P}\right)^{1/3}\frac{M_p \sin i}{(M_\star + M_p)^{2/3}}\frac{1}{\sqrt{1-e^2}}$$

$$M_p \sin i = \left(\frac{P}{2\pi G}\right)^{1/3} K_\star M_\star^{2/3}(1-e^2)^{1/2}$$

Direct Detection

$$B \geq \frac{\lambda D}{r} \approx \left(\frac{\lambda}{10\,\mu m}\right)\left(\frac{D}{10\,pc}\right)\left(\frac{r}{1AU}\right)^{-1} m$$

Effective Temperature

$$T_p = \frac{(1-A)^{1/4}}{\sqrt{2}}\left(\frac{R_\star}{r}\right)^{1/2} T_\star$$

$$A_\oplus \sim 0.39,\ T_\star \sim 5770\,K,\ r_\oplus \sim 1AU$$

$$\Rightarrow T_p \sim 280\,K \Rightarrow Greenhouse\ Effect!$$

Transit Method

$$\frac{\Delta F}{F} = \left(\frac{R_p}{R_\star}\right)^2,\quad t = \frac{P_p}{\pi}\left(\frac{R_\star \cos\delta + R_p}{a_p}\right)$$

$$i_{\min} = \cos^{-1}\left(\frac{R_\star}{a_p}\right),\quad \cos i = \frac{R_\star \sin\delta}{a_p}$$

If you wanted to observe the small dip in brightness as an exoplanet passes *behind* its host star, in which part of the spectrum would you look?

A. Infrared.
B. Visible.
C. Ultraviolet.
D. X-ray.

Exoplanet Discovery

- Extrasolar planets, or exoplanets, can be detected by astrometry, radial velocities (using the Doppler effect), transits, microlensing, and direct detection.

- By far the most successful techniques have been ground-based radial velocity searches and space-based transit searches (about 3,000 exoplanets confirmed).

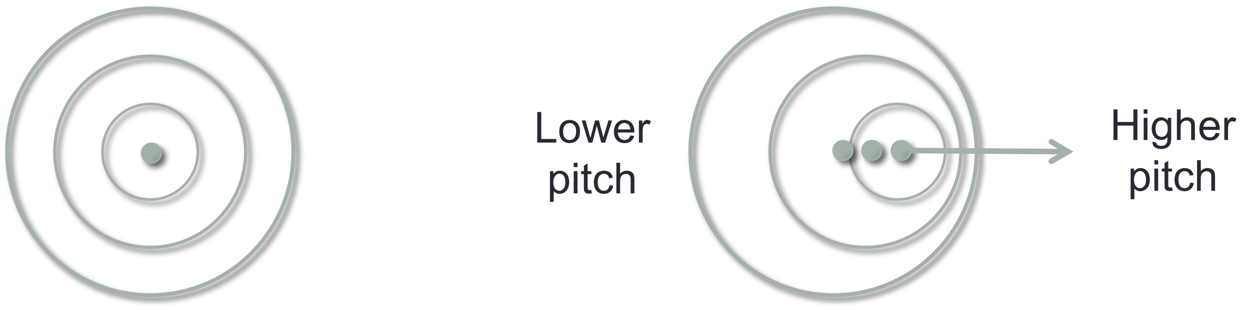
- Both techniques give the period of the orbit, and so the semimajor axis. Radial velocities give the mass. Transits give the radius. Together they give the density.

Selection Effects

- ***Extremely*** important in astronomy!
- The most common things you see in the sky are a combination of (1) the things that are actually the most common, and (2) the things that are easiest to see
- For the radial velocity and transit methods:
  Is it easier to see high-mass or low-mass planets?
  Planets with large or small diameters?
  Planets that are close-in or far from their host star?
- What about for other planetary detection methods?
- In astronomy, what you see is ***not*** what you get! This must be kept very clearly in mind when we study the universe...

How does light tell us the speed of a distant object?

- From our everyday experience with sound waves:
  - Approaching sound emitter has higher pitch (shorter wavelength).
  - Receding sound emitter has lower pitch (longer wavelength).



Stationary emitter, frequency f

Moving emitter, speed v

$$\Delta\lambda = v\left(\frac{1}{f}\right) = v\left(\frac{\lambda}{c_s}\right) \text{ or } \boxed{\frac{\Delta\lambda}{\lambda} = \frac{v}{c_s}}.$$

How does light tell us the speed of a distant object?

- From our everyday experience with sound waves:
  - Approaching sound emitter has higher pitch (shorter wavelength).
  - Receding sound emitter has lower pitch (longer wavelength).
- Same thing for light!
  - Approaching emitter looks *bluer* (shorter wavelength) ➔ blueshift.
  - Receding light emitter looks *redder* (longer wavelength) ➔ redshift.
  - Quantitatively, if λ_{obs} is the observed wavelength and λ_{emit} is the emitted wavelength, then the speed is given by

$$\boxed{\frac{v_{\text{rad}}}{c} = \frac{\lambda_{\text{obs}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}}.}$$

Positive for redshift, negative for blueshift.

  - NOTE: this is only valid for $v_{\text{rad}} << c$ (non-relativistic limit).
  - Only gives component of v toward or away from observer (“radial”).

Going Deeper: Relativistic Doppler

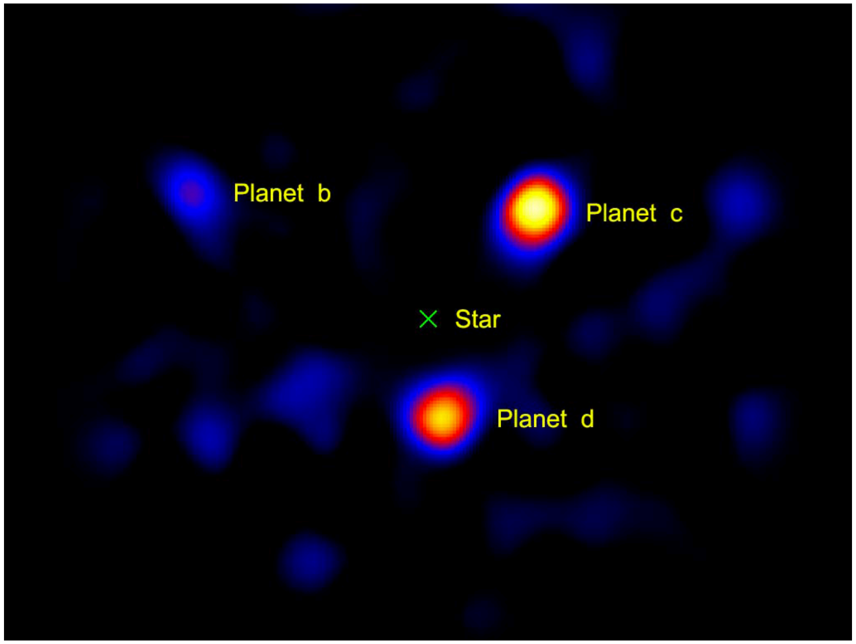
- What if we want to be exact?
- Suppose that the angle between the direction to the source, and the direction of motion of the source, is θ
- Let the speed of motion relative to the observer be v
- Then the observed frequency ν_{obs} is related to the emitted frequency ν_{em} by
  $\nu_{obs} = \gamma \nu_{em}[1-(v/c)\cos\theta]$
  where $\gamma=[1-(v/c)^2]^{-1/2}$; note that $v \cos\theta$ is the radial vel.
- Group Q: does this make sense in particular limits?
- Group Q: can we ignore the factor γ for stars and planets?
- Group Q: given that we care just about the total velocity, what about the drift of the system through space?

Exoplanets Today

- The first detection of a planet orbiting a Sun-like star was announced in 1995.
  But the first exoplanets were seen around a pulsar (1992)!
- Since then, about 3,000 exoplanets have been detected, with a further ~5,000 waiting to be confirmed.
- Many different techniques are used to find exoplanets—we will discuss the main ones.
- Searches have revealed a bewildering assortment of exoplanet properties, from "hot Jupiters" to "super Earths," that challenge planet-formation theories.
- The race is on to find "habitable" planets with "biomarkers" in their atmospheres. We may not have long to wait!…
  Our newest professor, Eliza Kempton, works on atmos

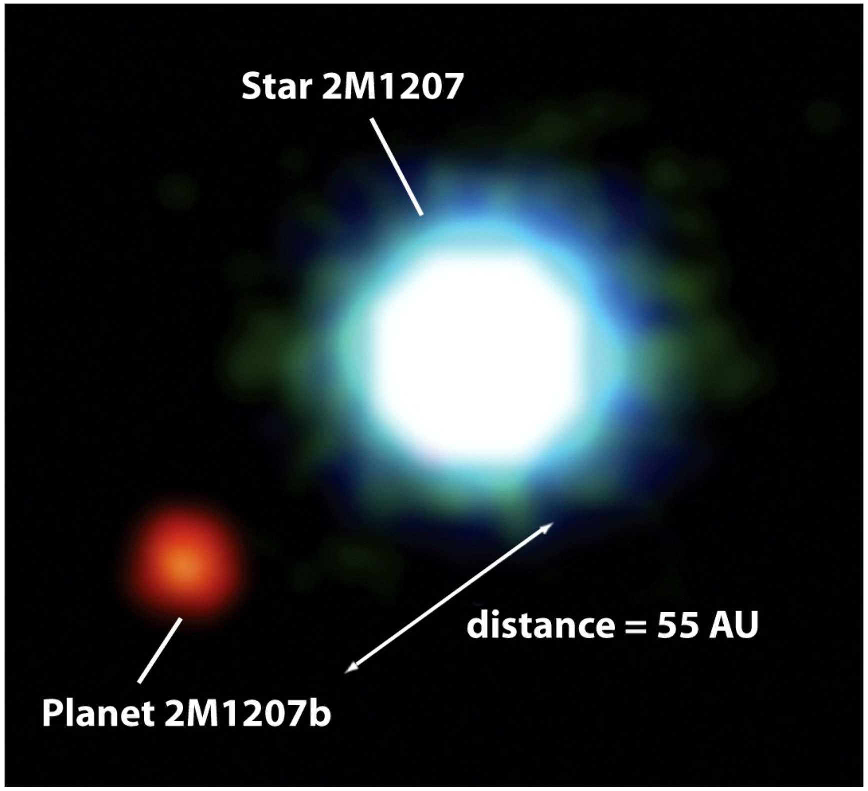
Detecting Exoplanets

- Difficult to observe: for example, the Sun is 10^9 times brighter than the Earth.
- Most extrasolar planets (exoplanets) are detected *indirectly* by measuring stellar properties that suggest planets in orbit.
    - Radial velocities & transits.
    - Astrometry & microlensing.
- Relatively few detections are *direct* (~40 so far).



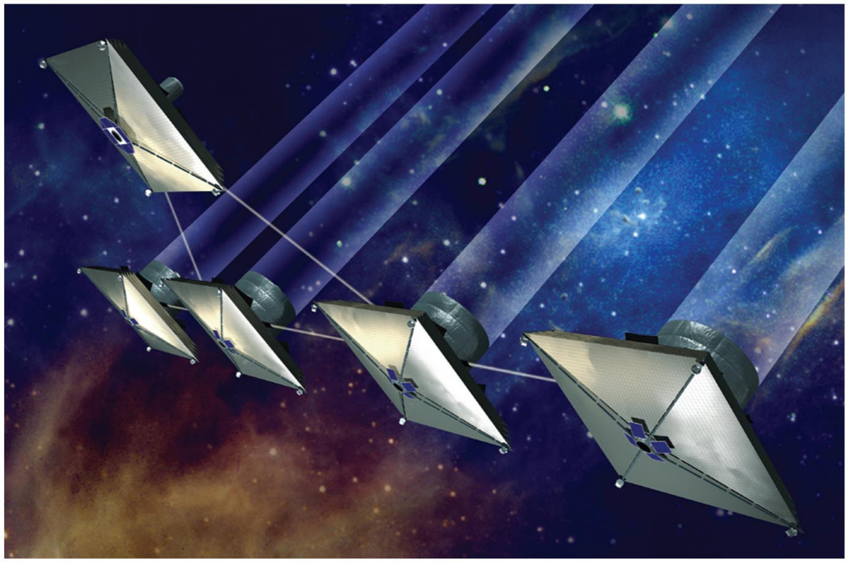
Direct image of exoplanets around HR8799 using Hale telescope *coronagraph* in near-IR.

Direct Detection



- Special techniques for concentrating or eliminating bright starlight are enabling the direct detection of planets (adaptive optics, coronagraphs, etc.).

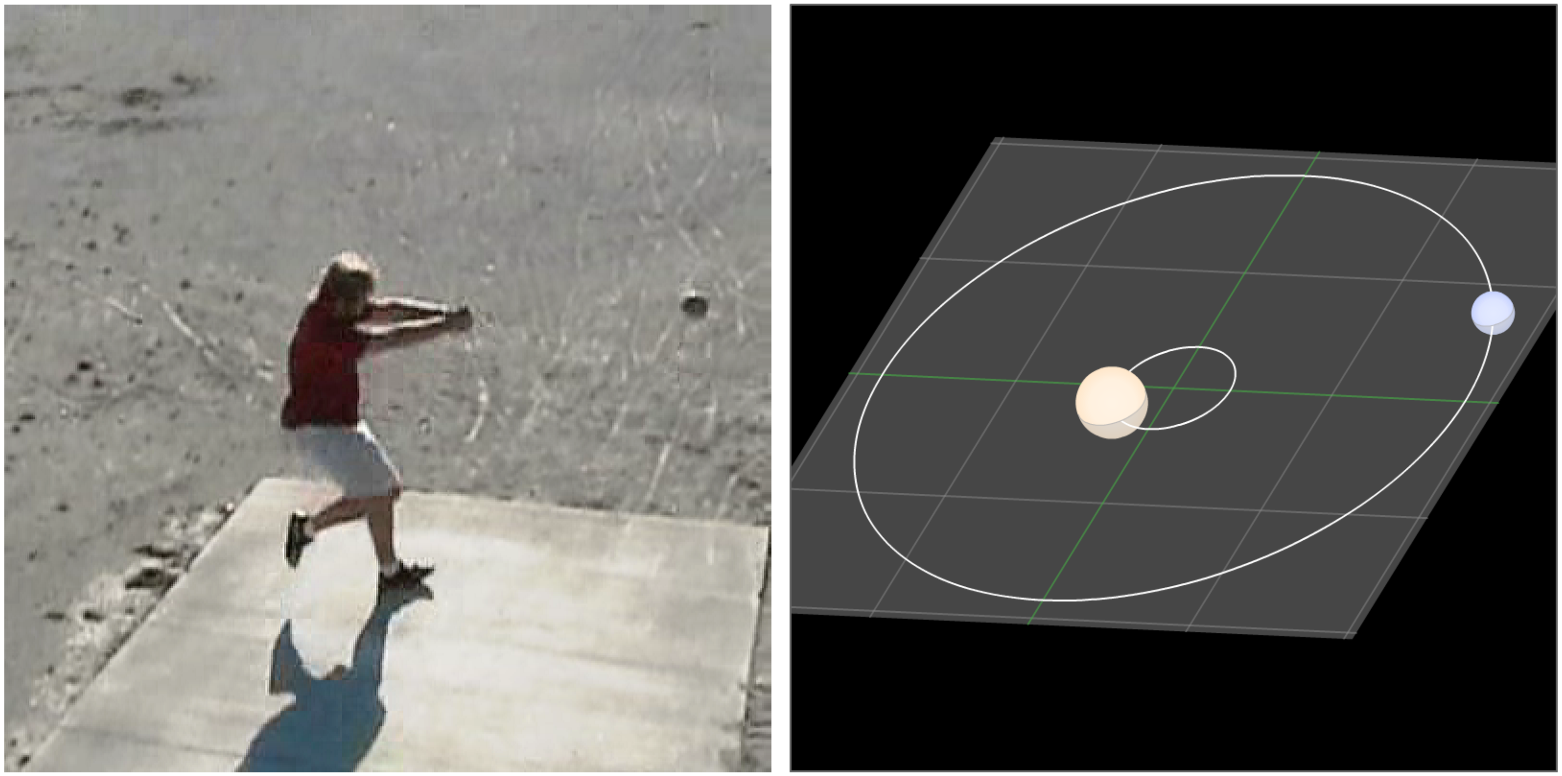
Direct Detection



Mission concept for NASA's Terrestrial Planet Finder.

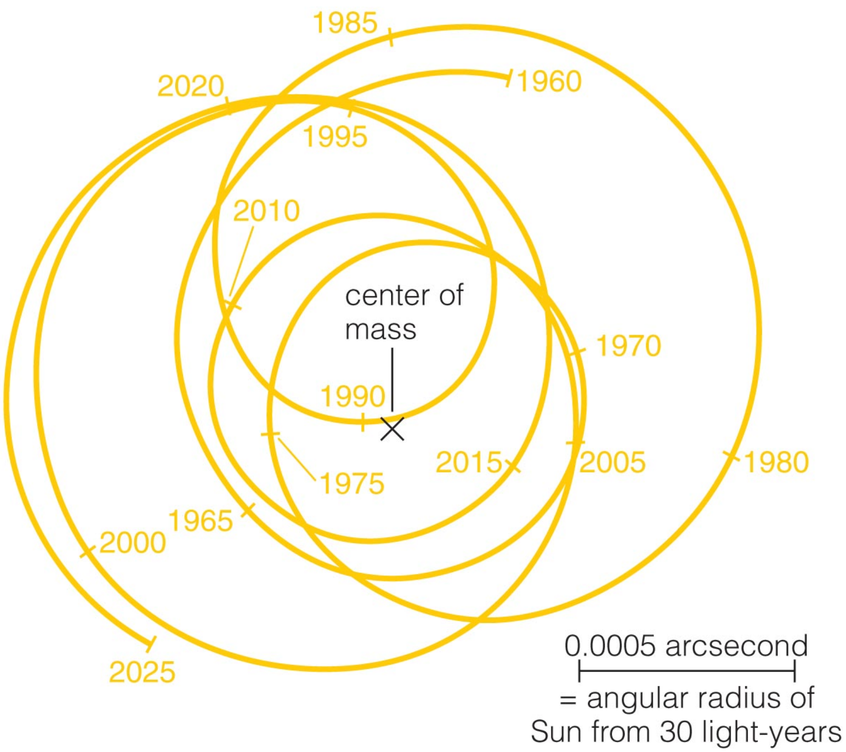
- Direct detection is easier above the atmosphere, but also very expensive.
- No current funded projects.

Indirect Detection



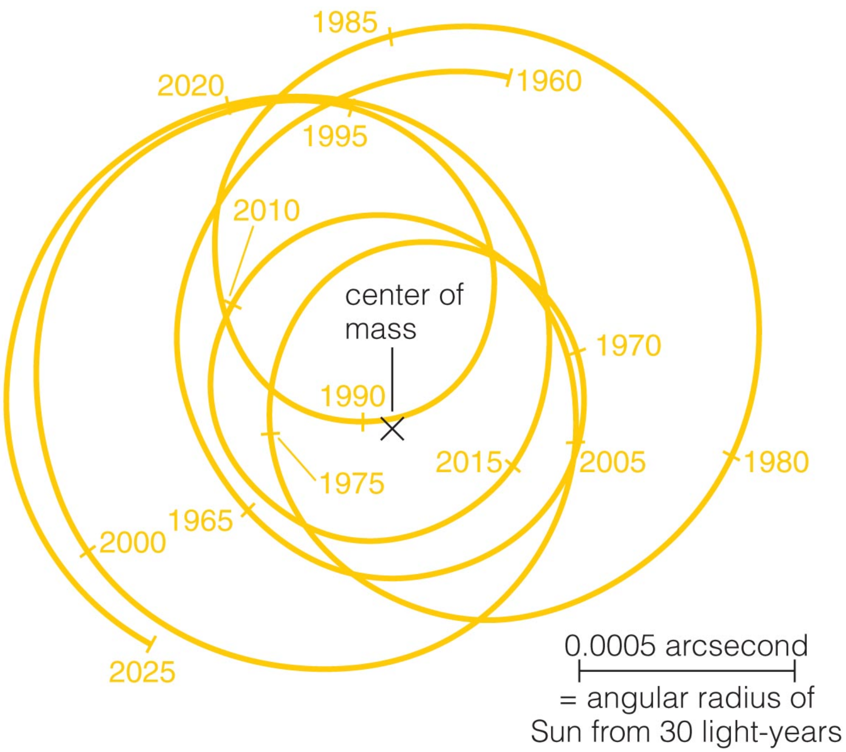
- Exoplanets and their host stars orbit a common *center of mass*.

Astrometric Technique



- The Sun’s motion around the solar system’s center of mass depends on tugs from all the planets.
- Astronomers around other stars who measured this motion could determine the masses and orbits of all the planets.

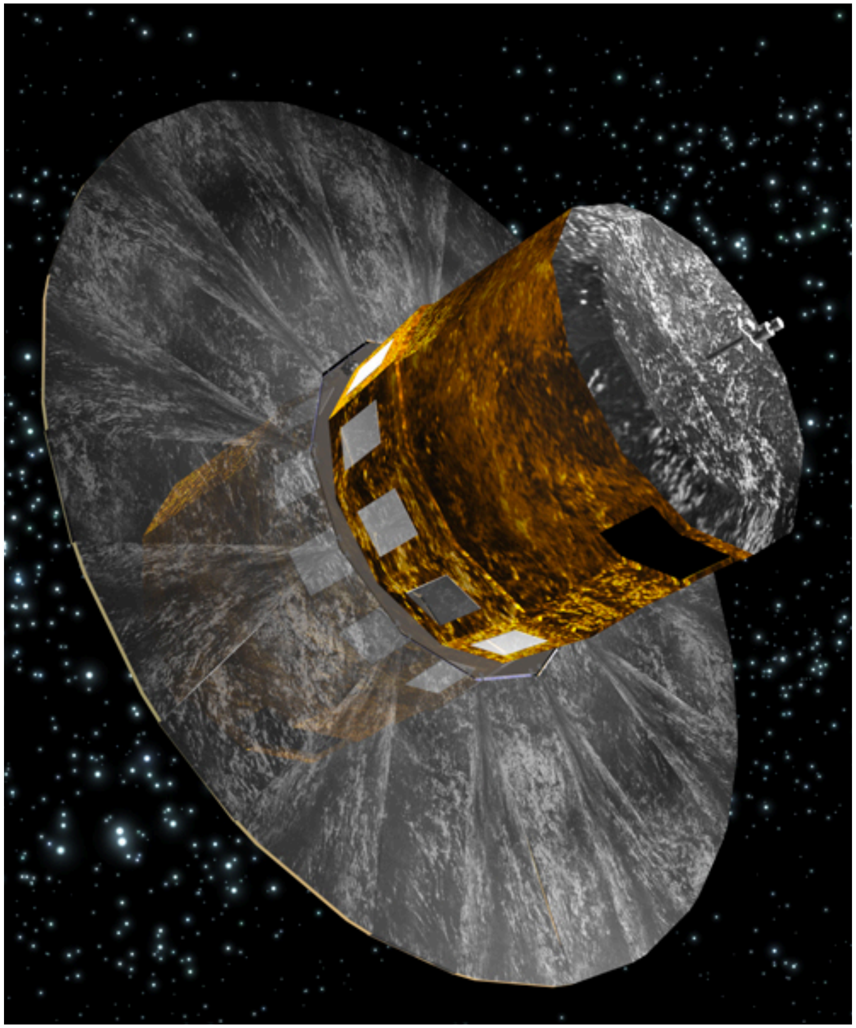
Astrometric Technique



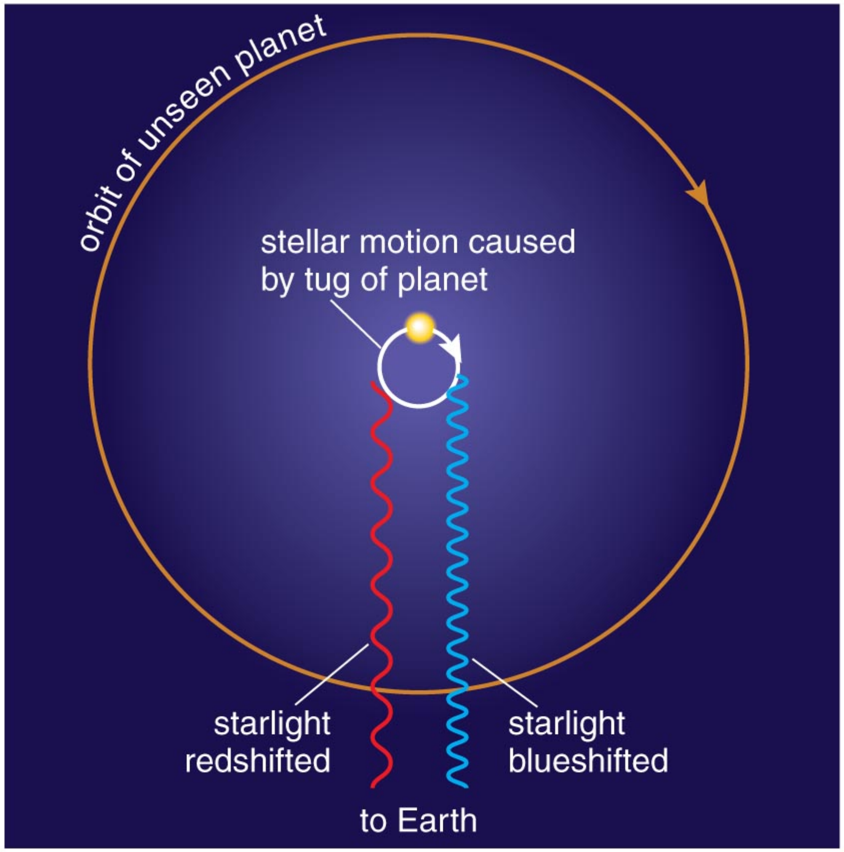
- We can detect planets by measuring the change in a star's position in the sky.
- However, these tiny motions are very difficult to measure (~0.001 arcsec, or 1 mas).
- So far only 1 exoplanet found with astrometry.

The Gaia Mission

- *Gaia*: a European mission launched in 2013 that is measuring precise 3-D positions of a *billion* stars in the Milky Way galaxy.
- It may detect *tens of thousands* of exoplanets by astrometry and transits over the next five years.
- Final catalog release scheduled for 2022 (to be confirmed).

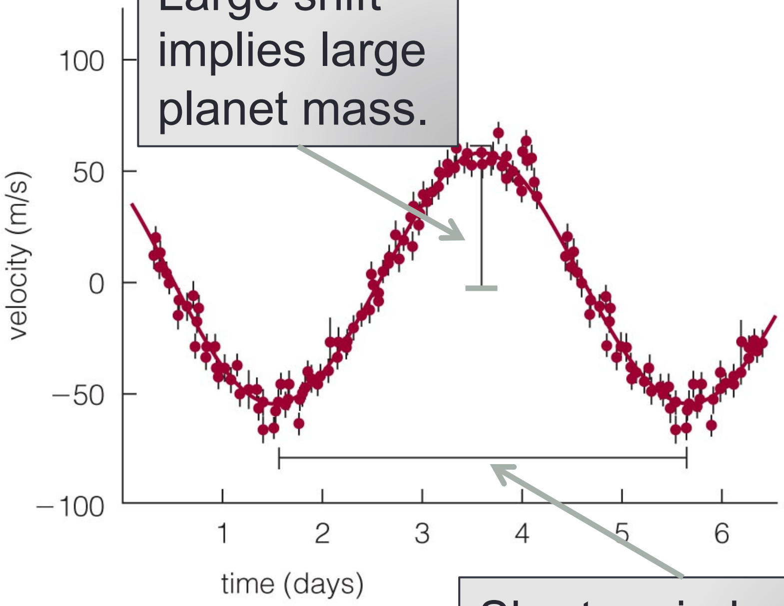


Doppler Technique (Radial Velocities)



- Measuring a star’s Doppler shift can tell us its motion toward and away from us.
- Current techniques can measure motions as small as 1 m/s (walking speed!).
- ~500 discoveries so far.

First Exoplanet Detected Around Normal Star



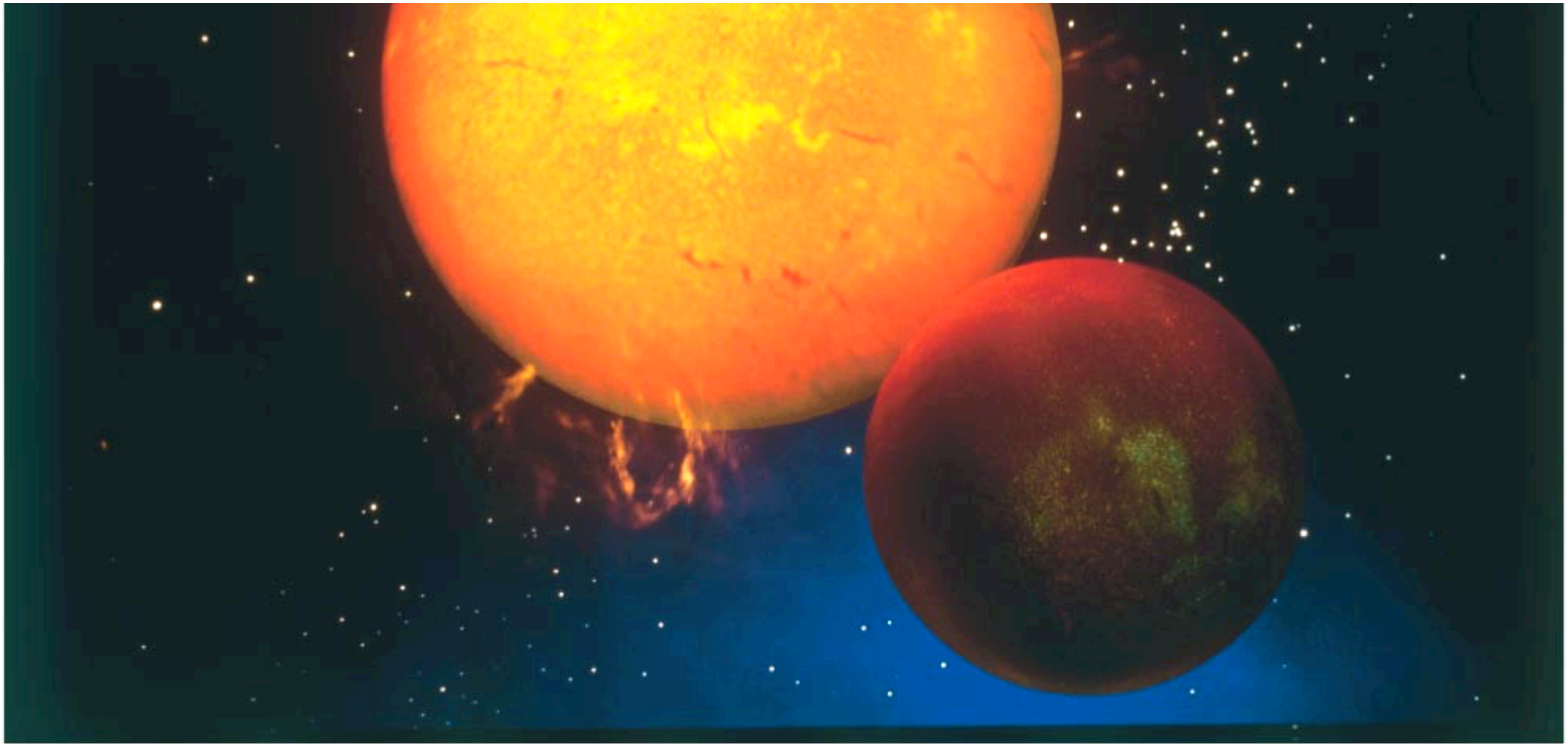
Large shift implies large planet mass.

Short period implies small orbit.

- Doppler shifts of star 51 Pegasi imply a planet with *4-day orbital period*.
- Short period means small orbital distance.
- First exoplanet to be discovered around a Sun-like star (1995).

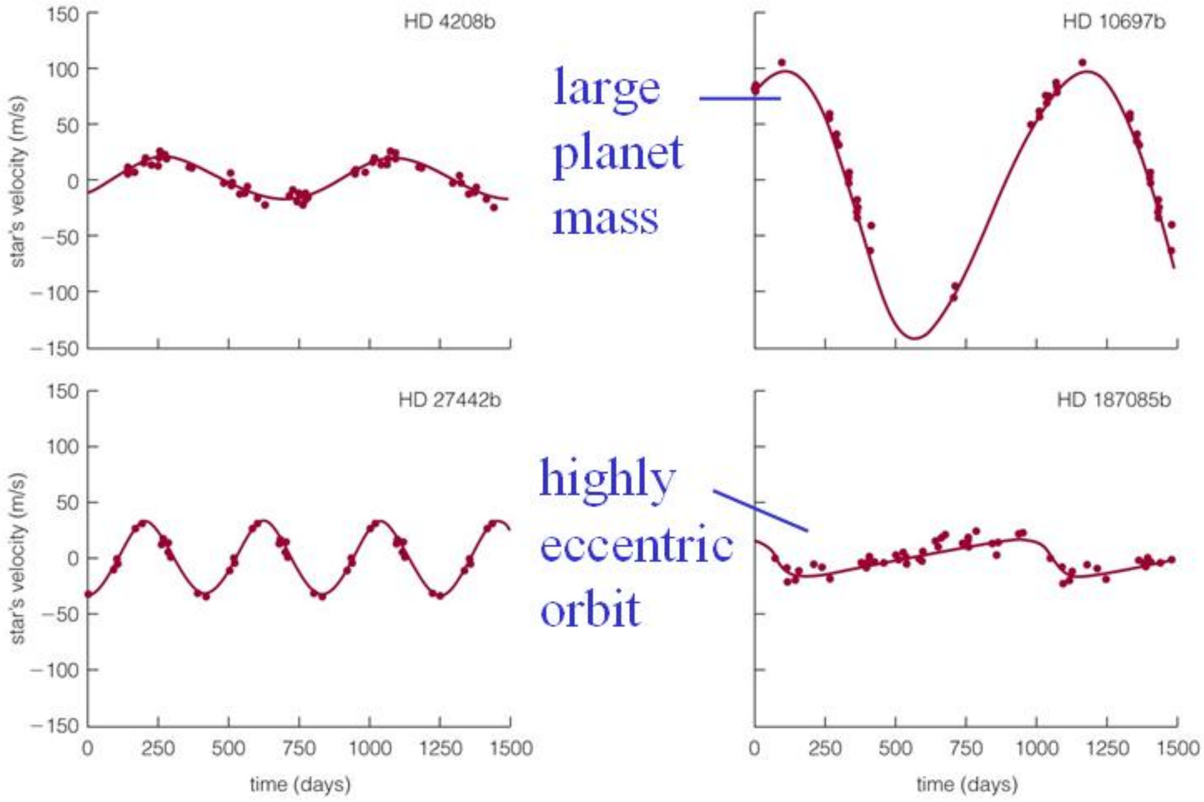
Important: “exoplanet” refers to planets around *stars*, not, e.g., pulsars (rotating neutron stars)—the first planet around a pulsar was detected in 1992.

First Normal-Star Exoplanet Detected



- The planet around 51 Pegasi has a mass similar to Jupiter’s, despite its small orbital distance. Surprising?

Other Exoplanets



- Doppler shift data tell us about a planet’s mass and the shape of its orbit.

Interpreting Radial Velocity Curves

- The oscillation *period* P gives the planet *semimajor axis* a via Newton's version of Kepler's 3rd law:

$$P^2 = \frac{4\pi^2}{GM_*}a^3.$$

Get star mass from spectral type—see ASTR121!

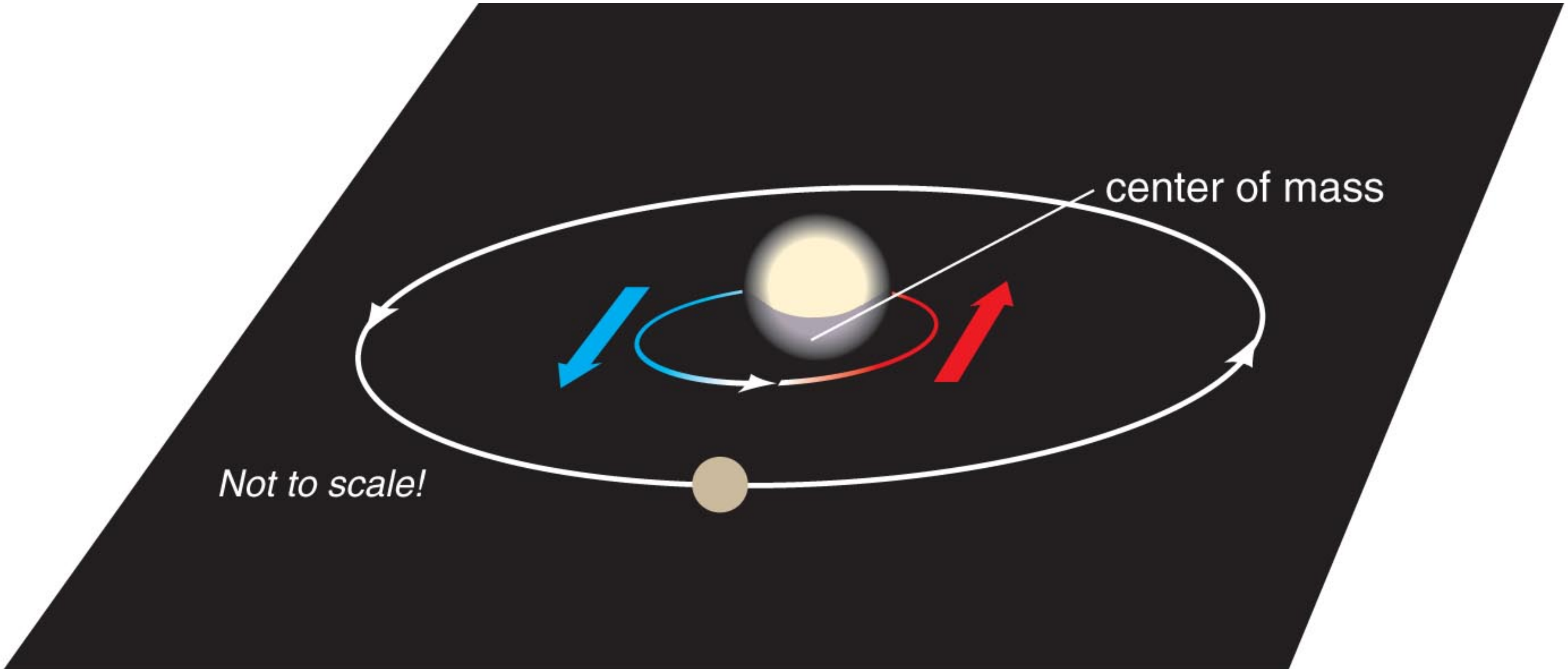
- The oscillation *amplitude* V_* (in units of speed) gives the planet *mass* M_p via momentum balance:

$$M_*V_* = M_pV_p, \text{ with } V_p = 2\pi a / P.$$

Assumes circular orbit, otherwise more complex approach needed.

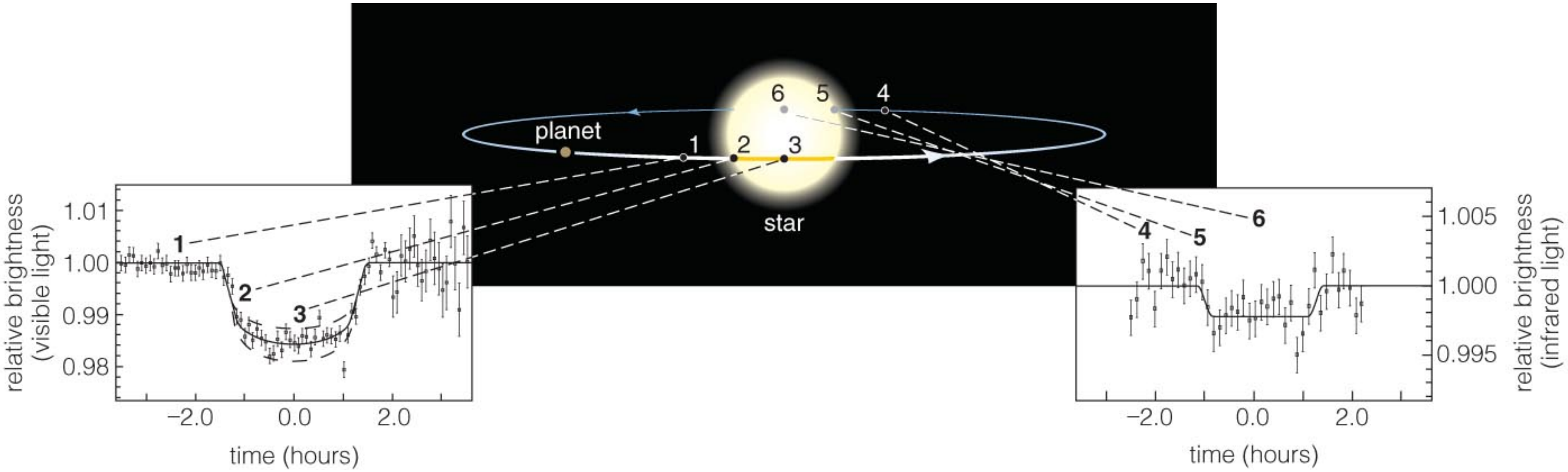
- The *shape* of the oscillation curve reveals the orbit *eccentricity* e (sine wave is a circle; sawtooth is eccentric).
- The presence of *multiple signals* implies *multiple planets*.

Planet Mass and Orbit Tilt



- With radial velocities, only get a *lower limit* to planet mass: $M_p = M_{\text{actual}} \sin(i)$, where i = orbit tilt along the line of sight ($i = 90°$ for edge-on orbit; $0°$ for face-on orbit).
  How might we determine the inclination?

Transits and Eclipses



- A ***transit*** is when a planet crosses in front of a star, resulting in a dip in brightness.
- An ***eclipse*** is also sometimes seen, when the planet passes behind the star.
- Essentially no orbital tilt ($i \sim 90°$), so we get an accurate measurement of the planet mass with radial velocity.

Transit of Venus (2012)