ASTR 620: Planetary Processes
Professor Eric Nielsen

Lecture 19: Atmospheres

Logistics

- Masks are encouraged

- No laptops, phones, or other electronic devices during class (I'll let you know in advance if we'll need laptops for an activity) **You may use a tablet to take notes if prefer, but please only use it for note-taking.**

- Remember to bring you response card to class

Review of the last class

- A rotating parcel of air is stretched in the vertical direction, as a result:

  - (A) — it rotates faster

  - (B) — it rotates in the opposite direction

  - (C) — it rotates slower

  - (D) — there's no change to its rotation

Review of the last class

- Gravity waves are a balance between:

  - (A) — Gravity and pressure

  - (B) — Buoyancy and pressure

  - (C) — Gravity and buoyancy

  - (D) — Tension on magnetic field lines and gravity

  - (E) — Tension on magnetic field lines and pressure

Review of the last class

- Gravity waves propagate:

  - (A) — Only in the horizontal direction

  - (B) — Only in the vertical direction

  - (C) — Usually in the horizontal direction, but sometimes also in the vertical direction

 - (D) — Gravity waves never propagate

Review of the last class

- Potential vorticity and potential temperature:

  - (A) — Are never conserved

  - (B) — Are always conserved

  - (C) — Are conserved in a parcel only if no energy enters or leaves

  - (D) — Are conserved in a parcel only if the pressure stays the same

  - (E) — Are conserved in a parcel only if the density stays the same

Review of the last class

- Gravity waves only form near topographical features on solid surfaces, like mountains.
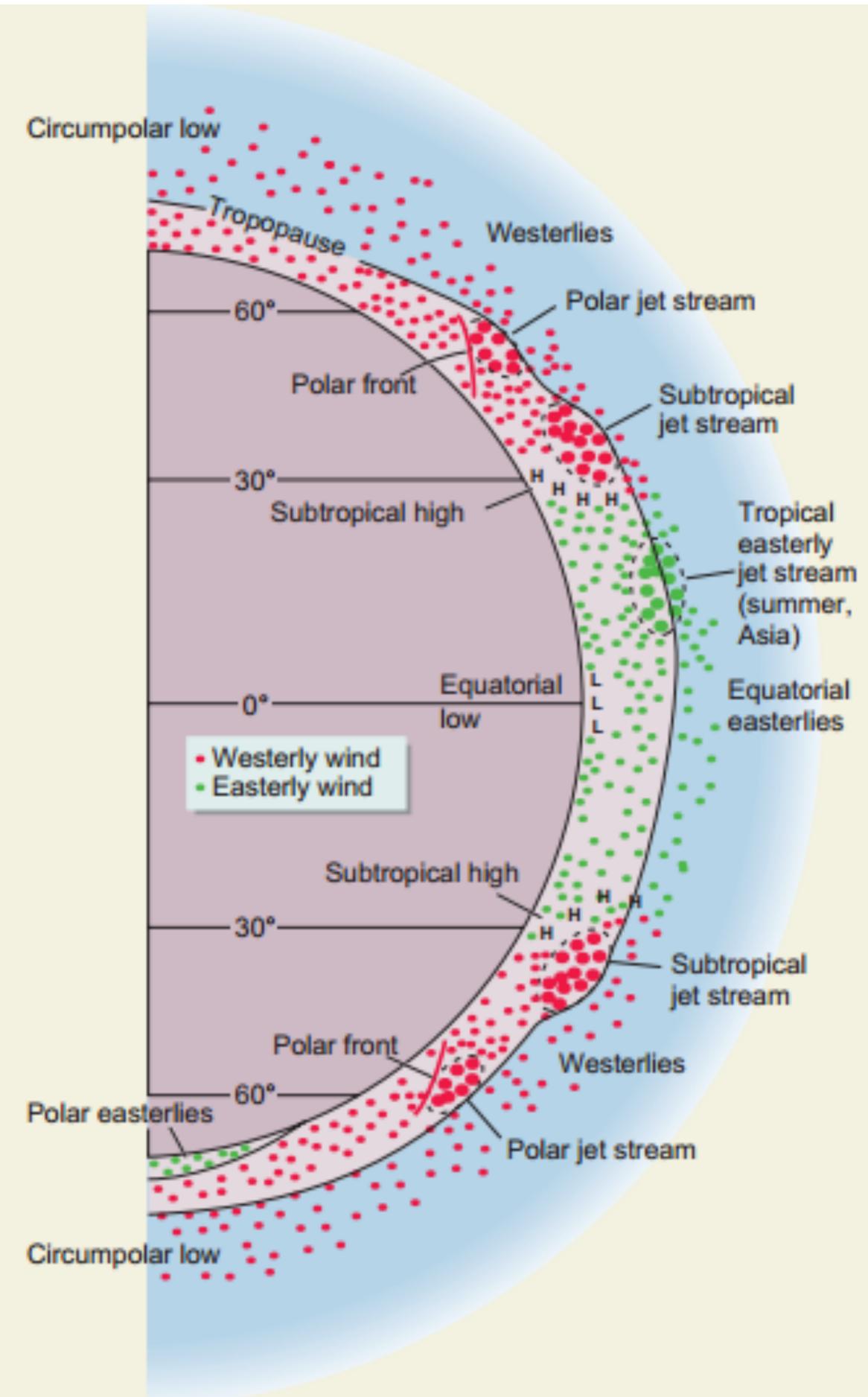
  - (A) — True

  - (B) — False

Jet Streams

- Wind streams that reach high speeds at narrow zones at high altitude

- Occur where pressure gradients are strong
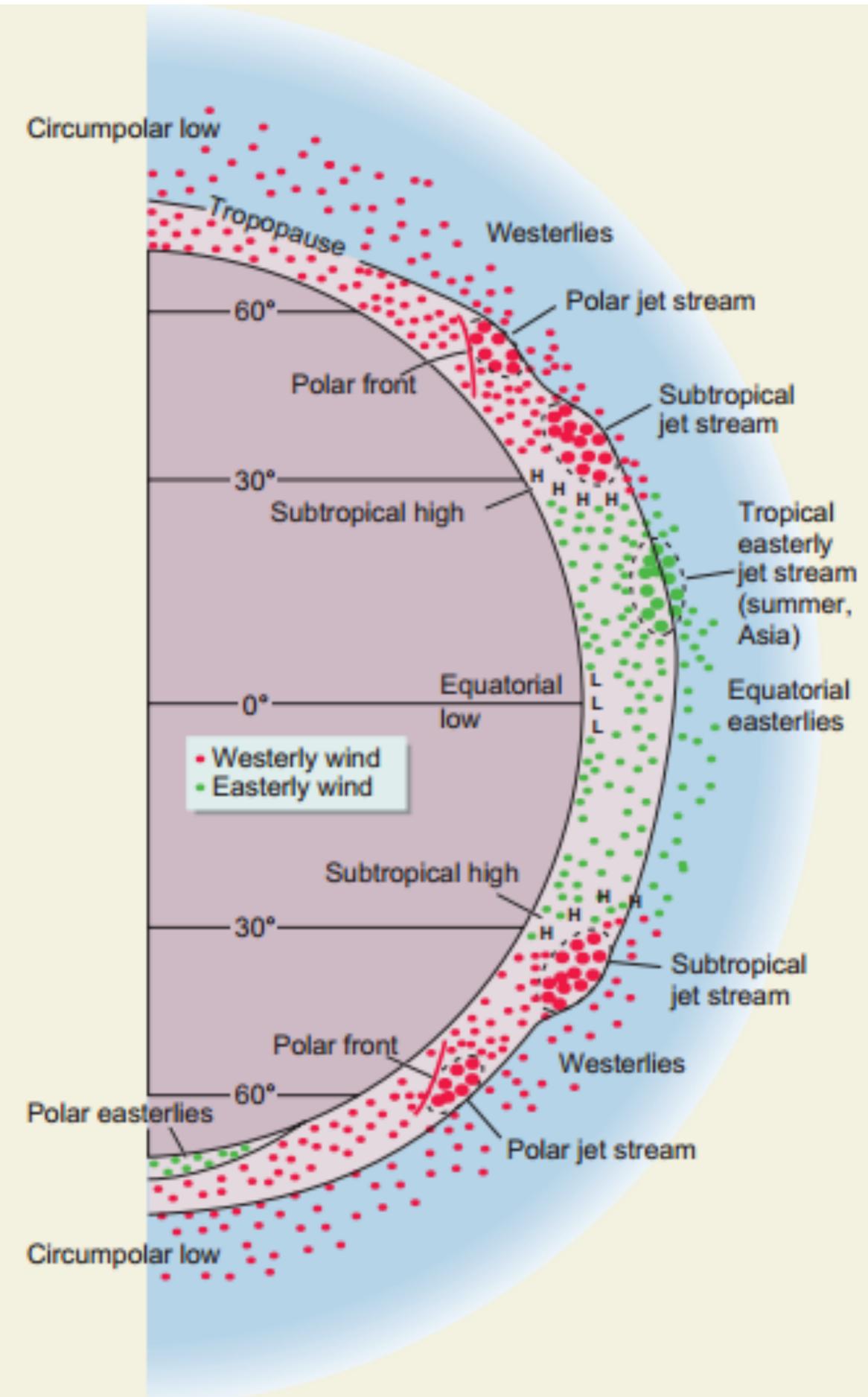
Jet Streams

- Westerly polar jet stream and subtropical jet stream

- Easterly tropical jet stream, near equator

- Rossby waves are disturbances in the jet streams

Rossby Waves

- Warmer air produces higher pressure above while cooler air produces lower pressure above

- Pressure differences produce disturbances in jet stream

- This disturbance circulates geostrophically around pressure centers
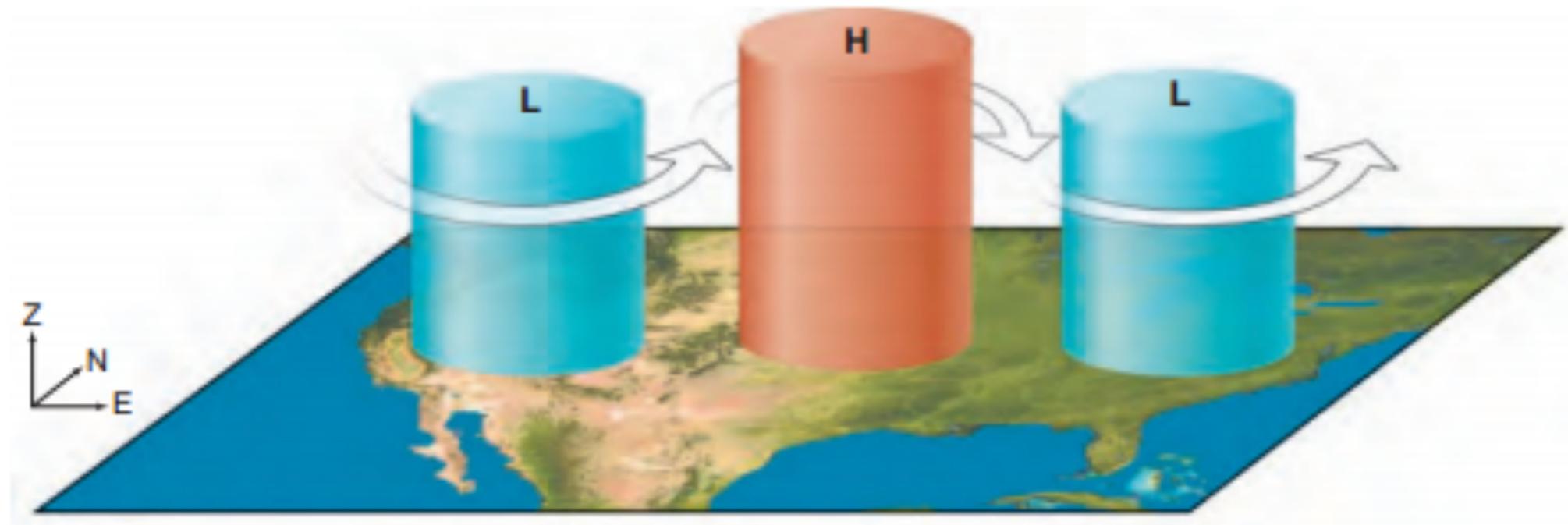
Response Card Question

- The vorticity of the three cells in this diagram are:

  - (A) — H: positive, L: negative

  - (B) — L: positive, H: negative

  - (C) — All positive

  - (D) — All negative
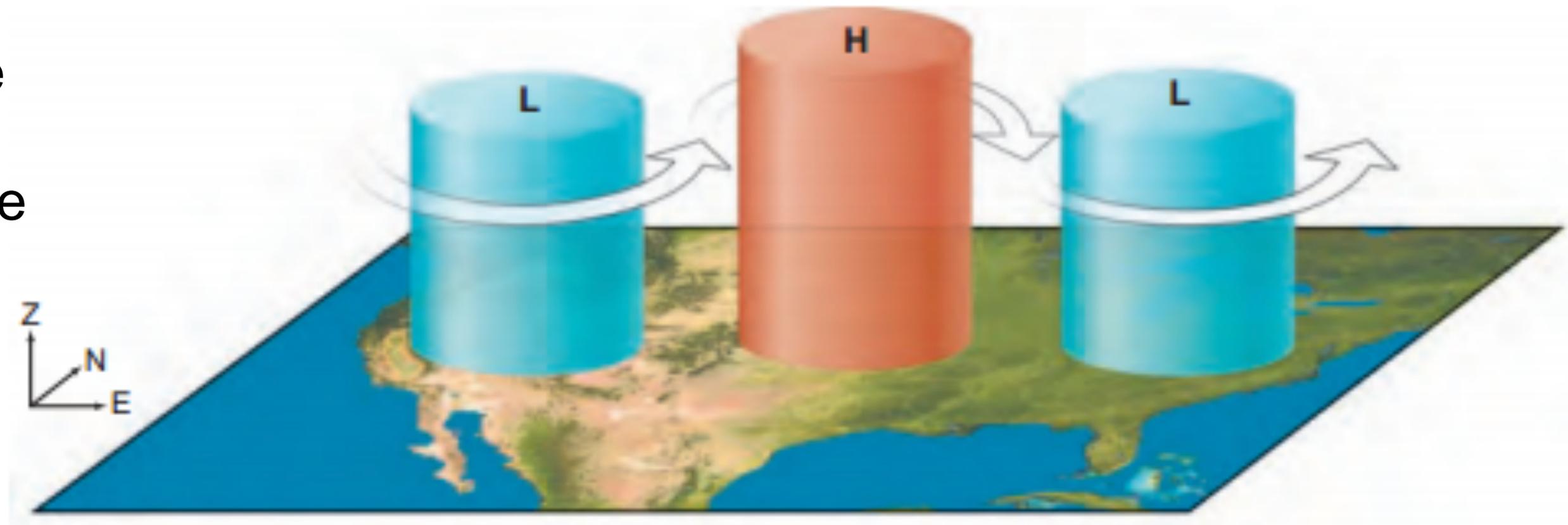
Rossby Waves

- Change in temperature between locations results in disturbance in north-south temperature gradient

- Counter-clockwise flow around low pressure brings warm tropical air from south close to the warm air column, resulting in further heating

- And the reverse: clockwise flow around high pressure bring colder polar air from the north to the cold air column, resulting in further cooling
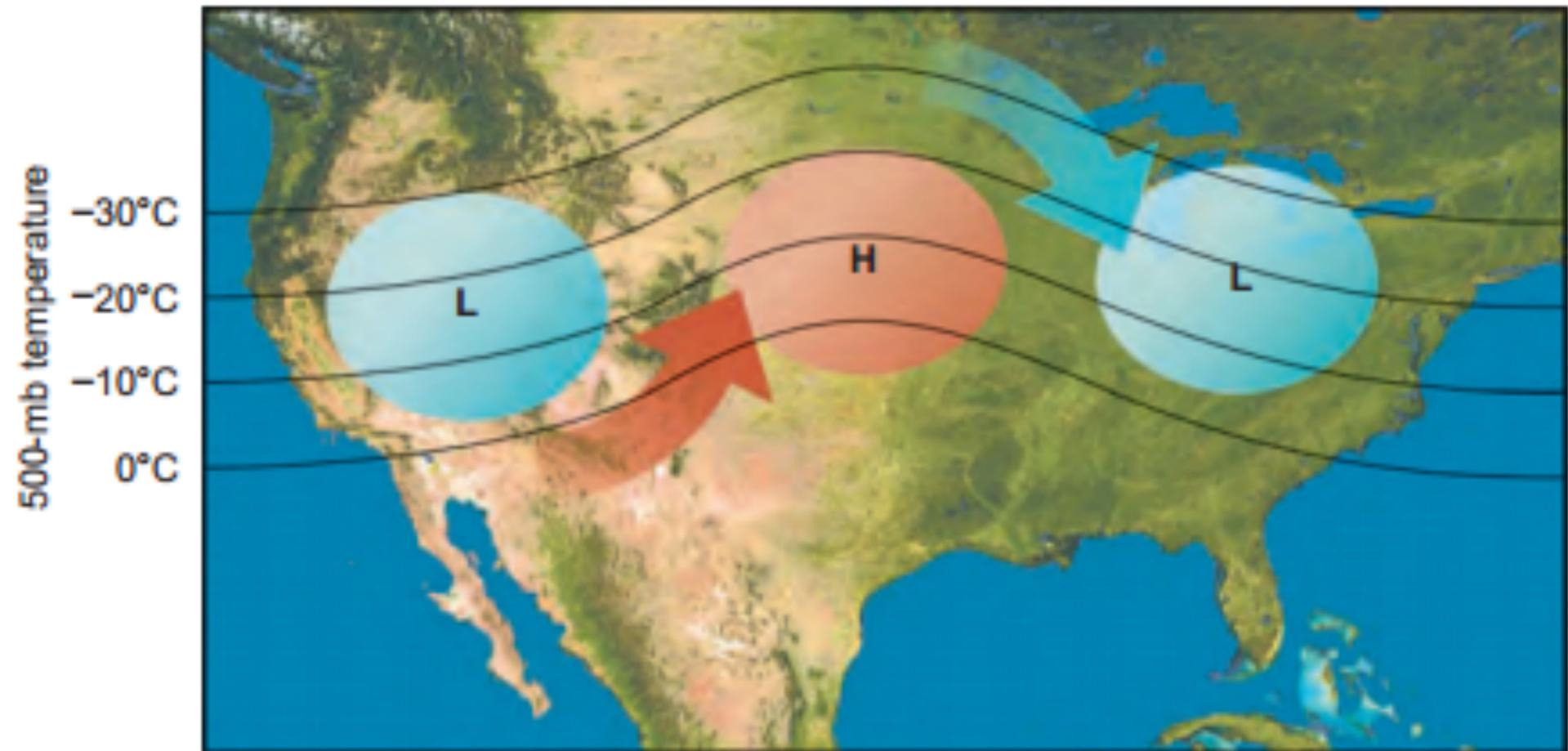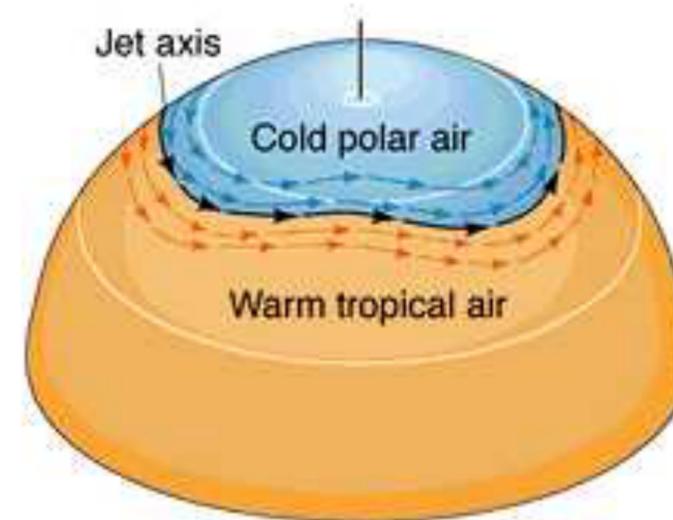
Rossby Waves

- Cycle continues (as warm air column warms further, expands and produces even higher pressures above)

- Pressure gradient between warm and cold regions intensifies, and so wind speeds also intensify (geostrophic conditions)
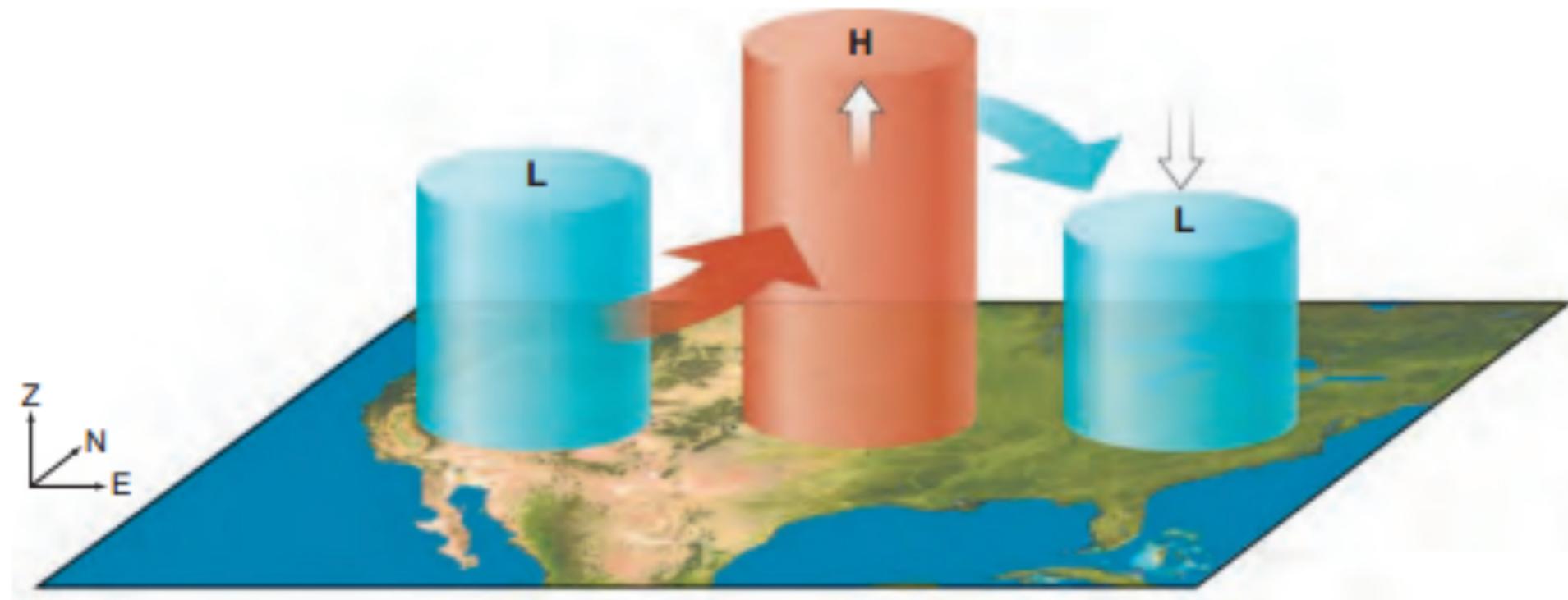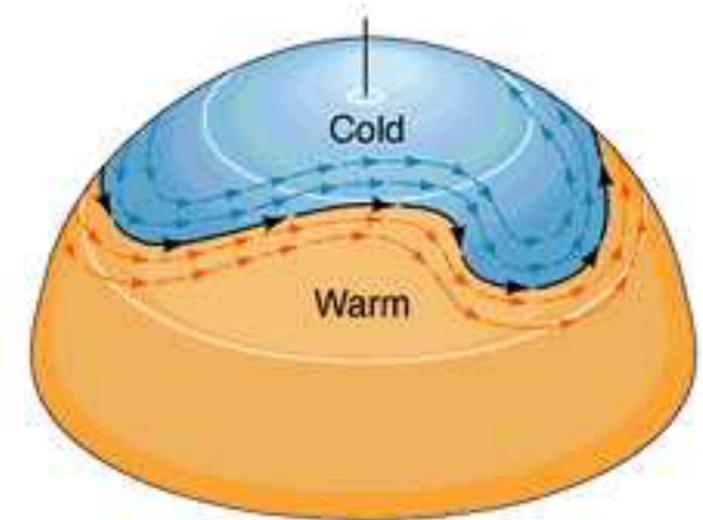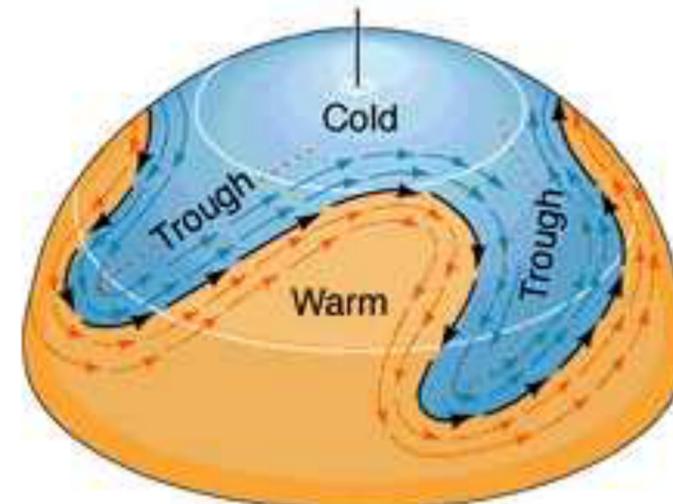
Rossby Waves

- Process is a positive feedback loop, but it does not continue indefinitely

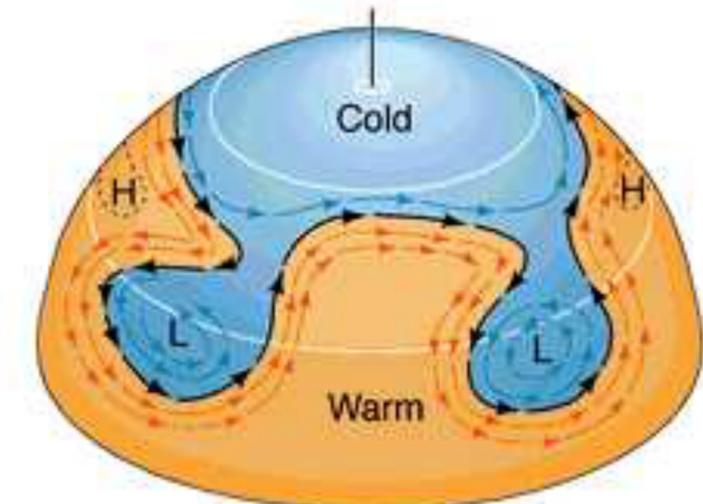- Eventually cold/warm regions get pinched off and dissipate

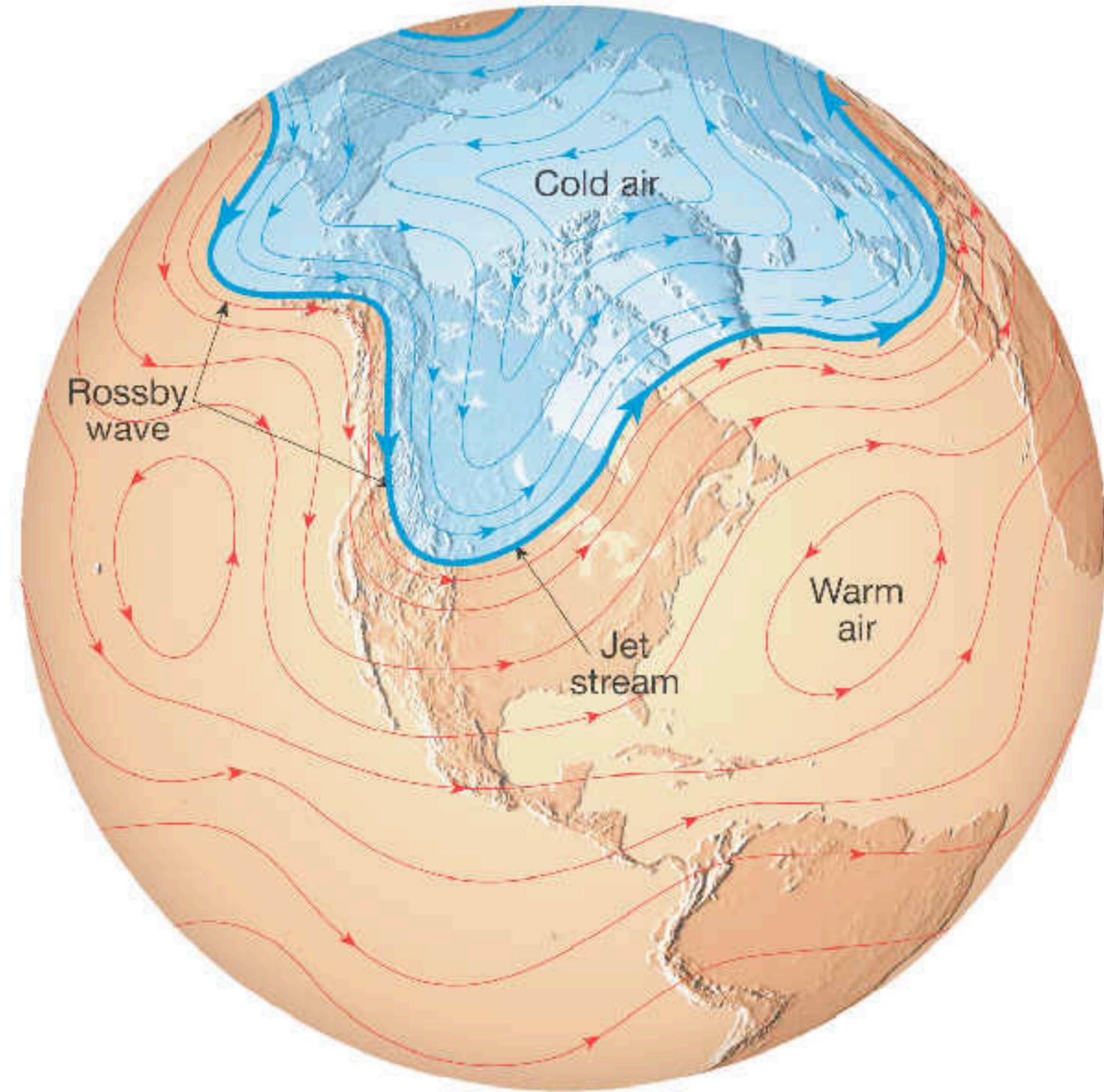The jet stream begins to undulate.

Rossby waves begin to form.

Waves are strongly developed. The cold air occupies troughs of low pressure.

When the waves are pinched off, they form cyclones of cold air.

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Rossby Waves

- Northern jet stream "meanders"

Rossby Waves

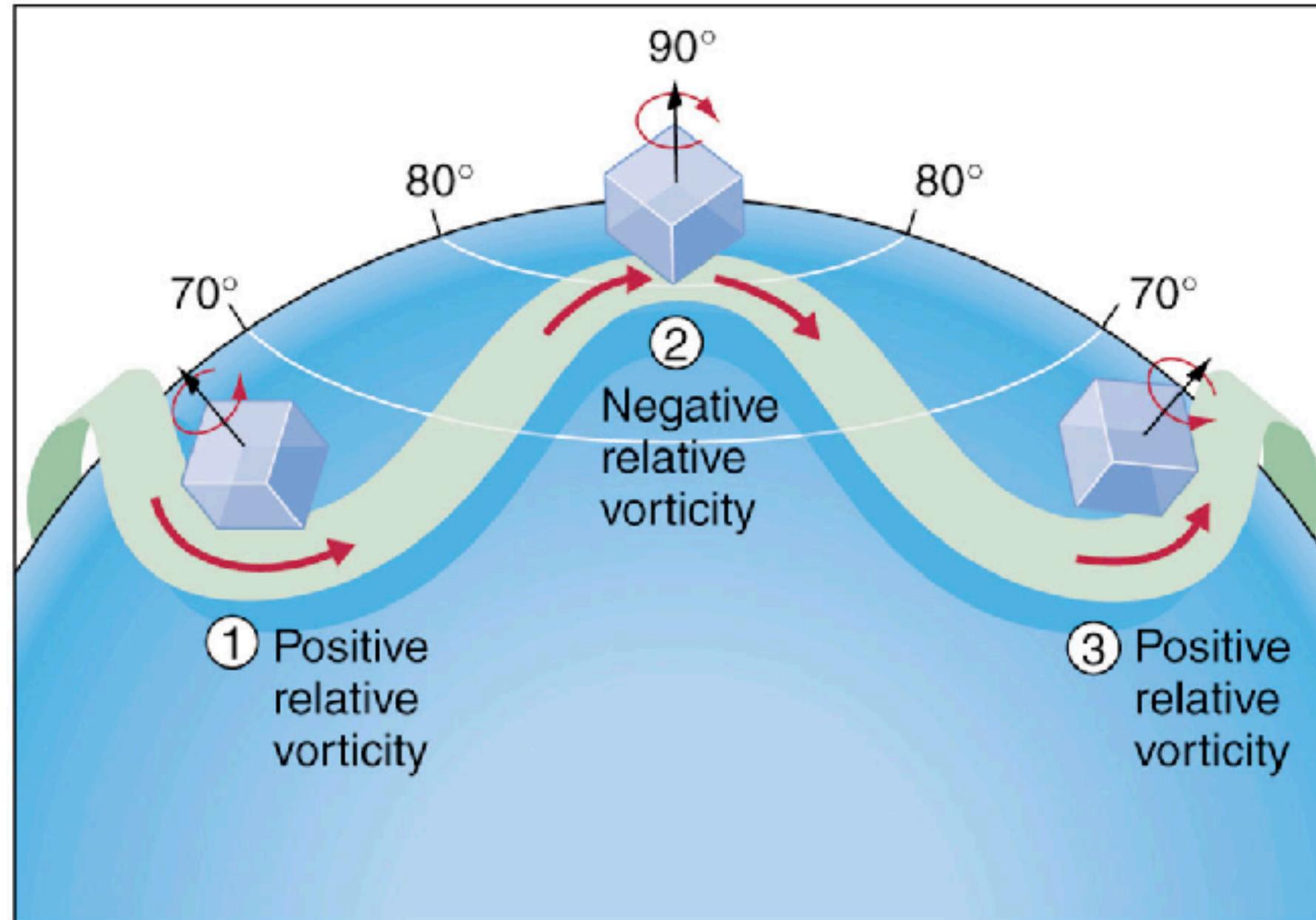- (1) Start with flow moving in South-east direction

$$\eta = \xi + f$$
$$\xi = 0$$
$$\eta = f$$

- Planetary vorticity decrease at lower latitude

  - Air columns spinning faster than surface, produce cyclonic curvature (positive vorticity) in trough

- $\eta = \xi + f$
  $\xi > 0$

Rossby Waves

- (2) Flow heads north, becomes straight again
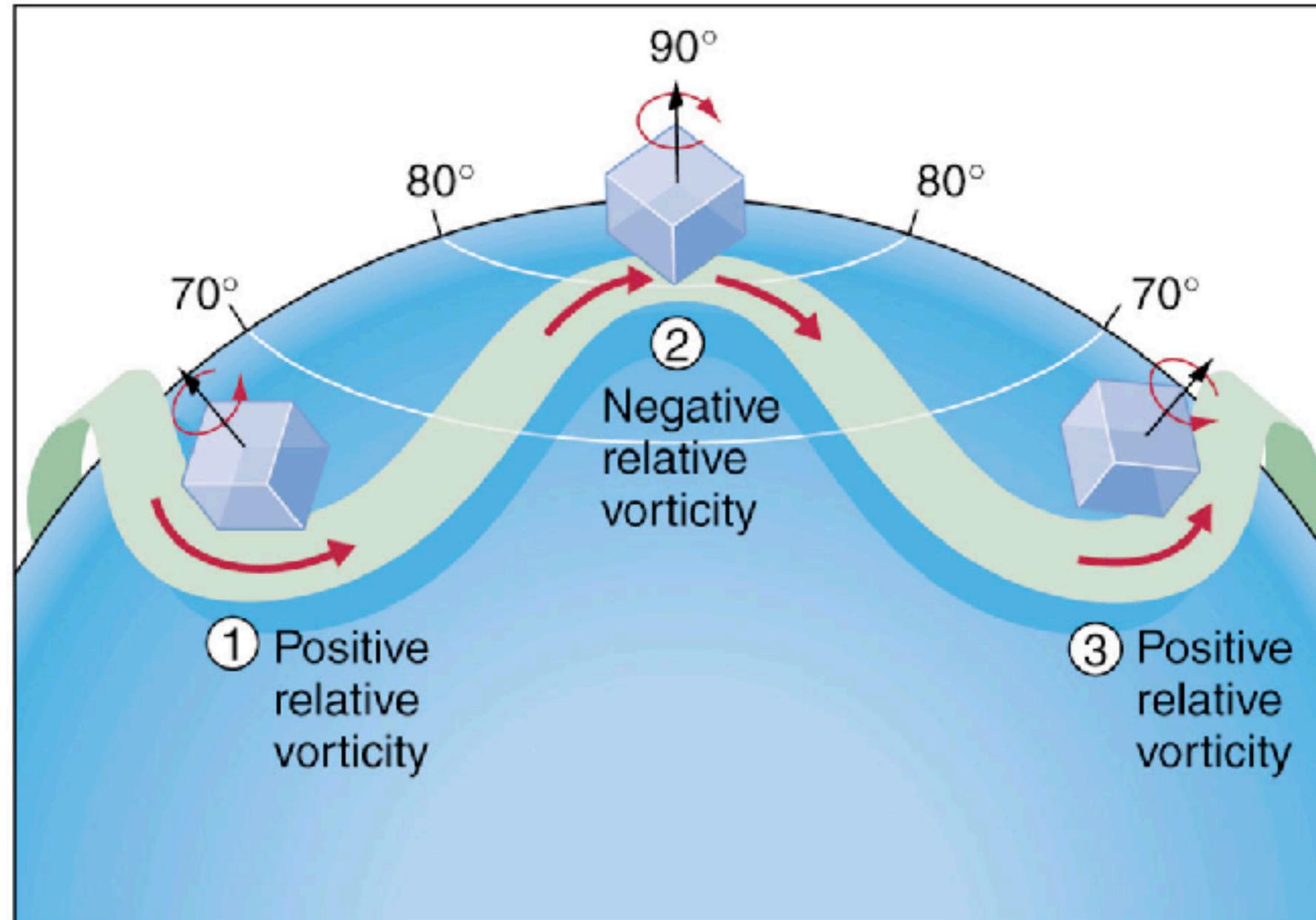
$$\eta = \xi + f$$
$$\xi = 0$$
$$\eta = f$$

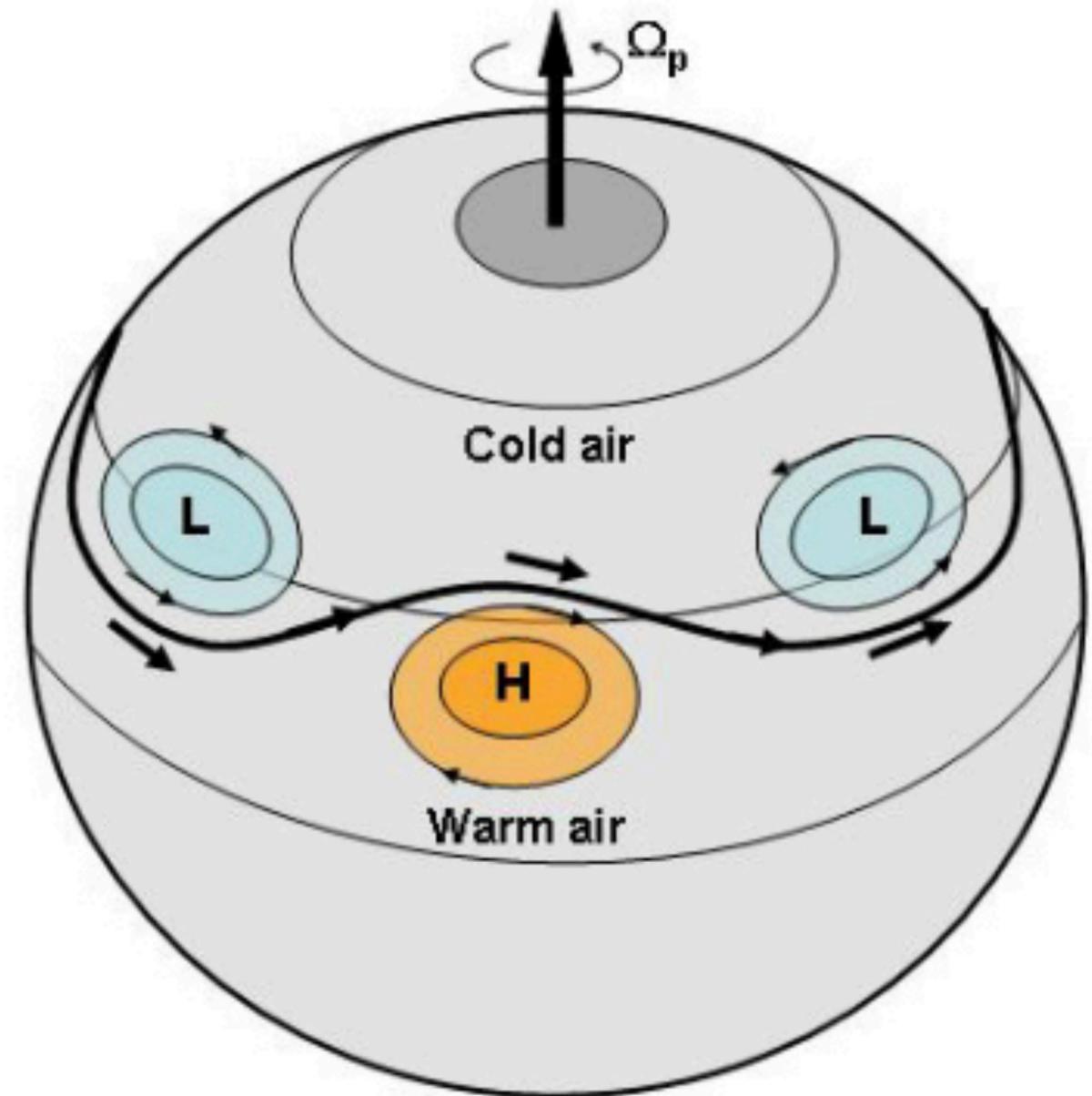- Planetary vorticity increase at higher latitude

  - air columns spinning slower than surface, produce anticyclonic curvature in crest
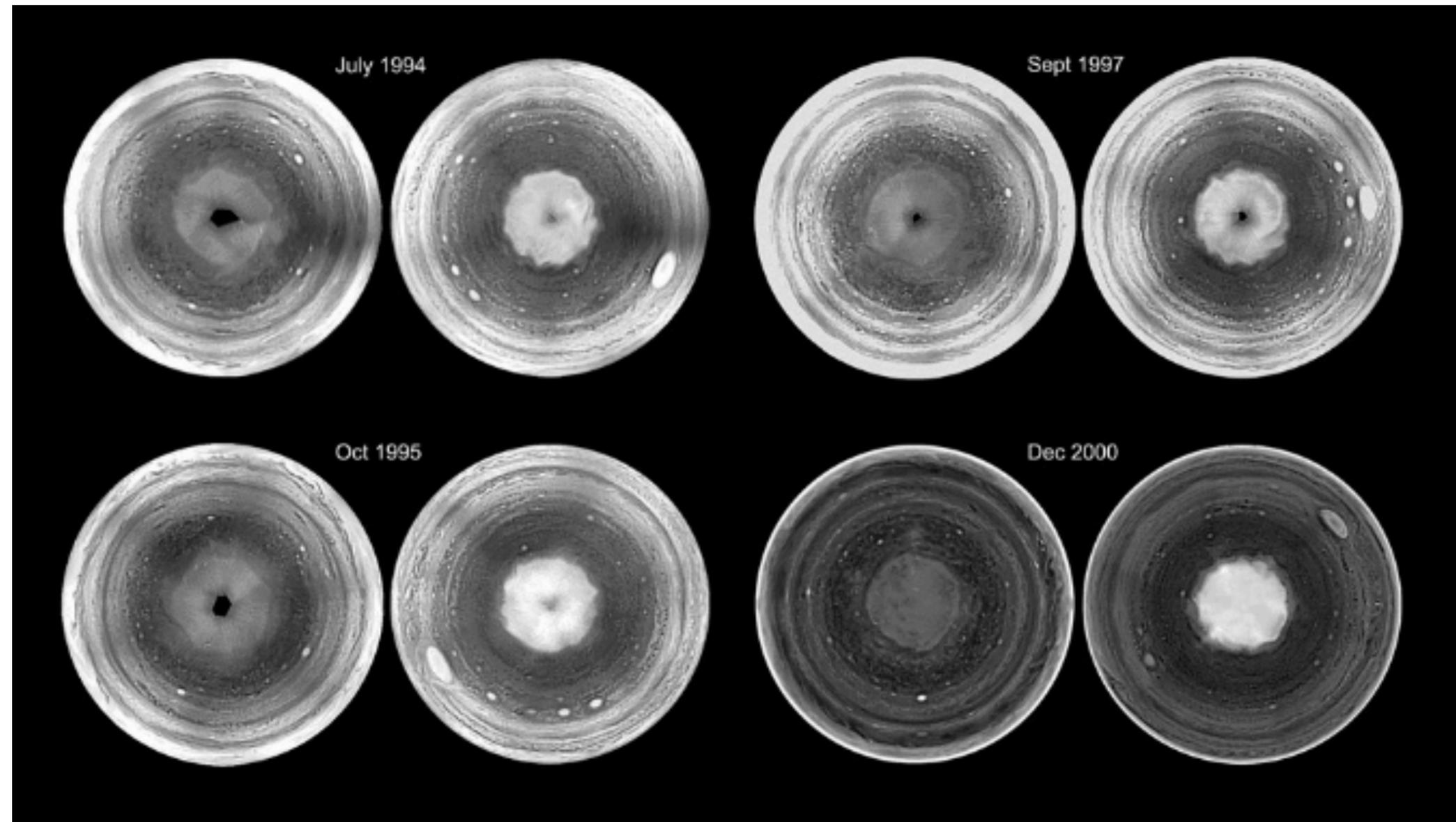
- $\eta = \xi + f$
  $\xi < 0$

Rossby Waves

- Cold air occupies troughs of low pressure (cyclones)

- Warm areas of high pressure (anticyclones) are found in crests

- Rossby waves are permanent phenomena in the Earth's mid and sub-polar latitudes

Jupiter

- "South polar wave" — wavy boundary of high altitude polar haze

Saturn

- Hexagon of jet streams at Saturn's southern pole: very stable feature

- Hexagon like a result of stable vortices forming around the hexagon boundary

- Movie from Cassini shows Rossby waves modifying exit shape of hexagon over time
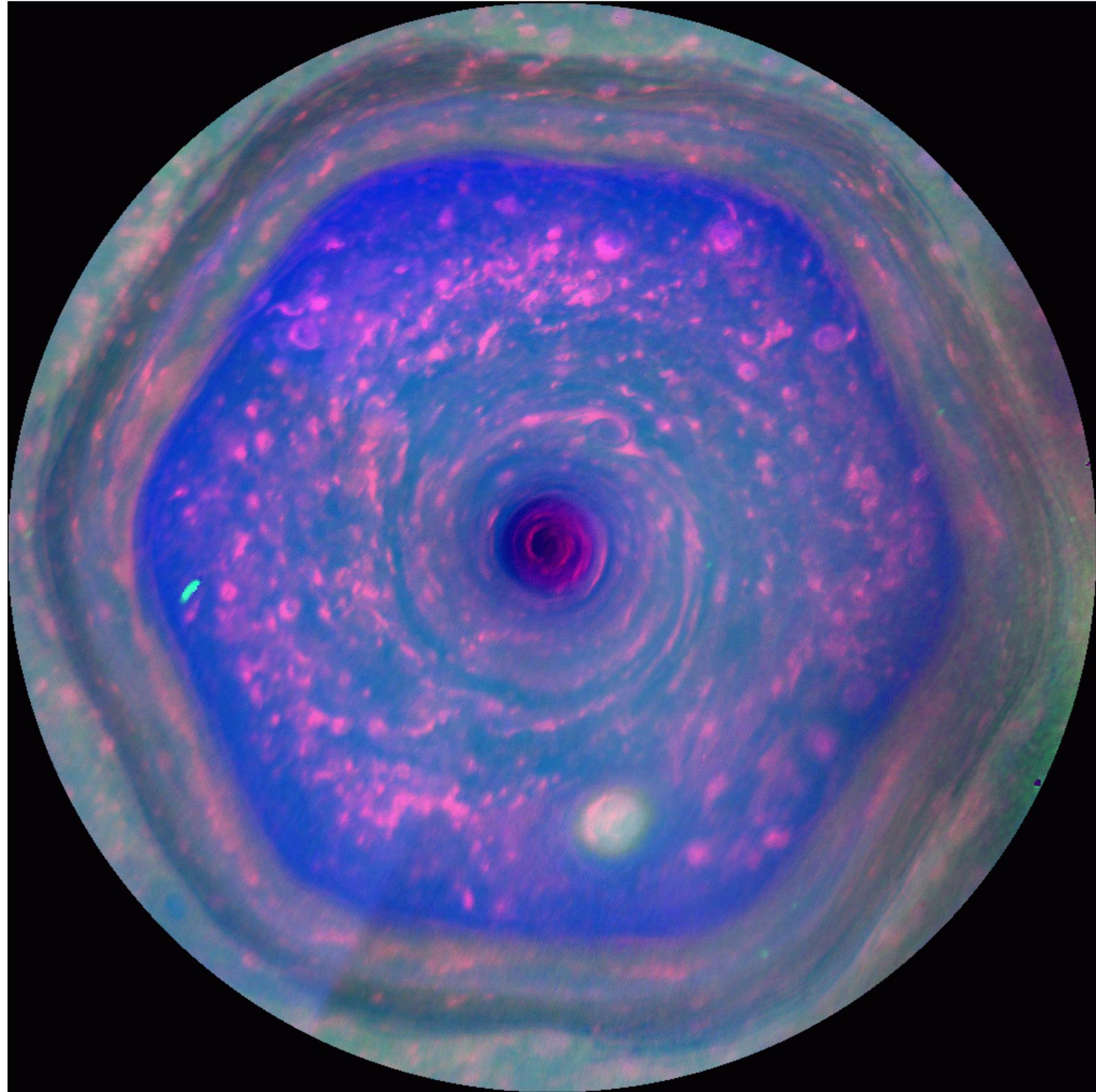
Solar Sytem Planets

- Until early 1990s, our solar system was the only example of planets known

- Starting in ~1992 planets started to be found around other stars with indirect methods

  - Extrasolar planets or exoplanets

  - (some disagreement on what the "first" exoplanet discovered was)
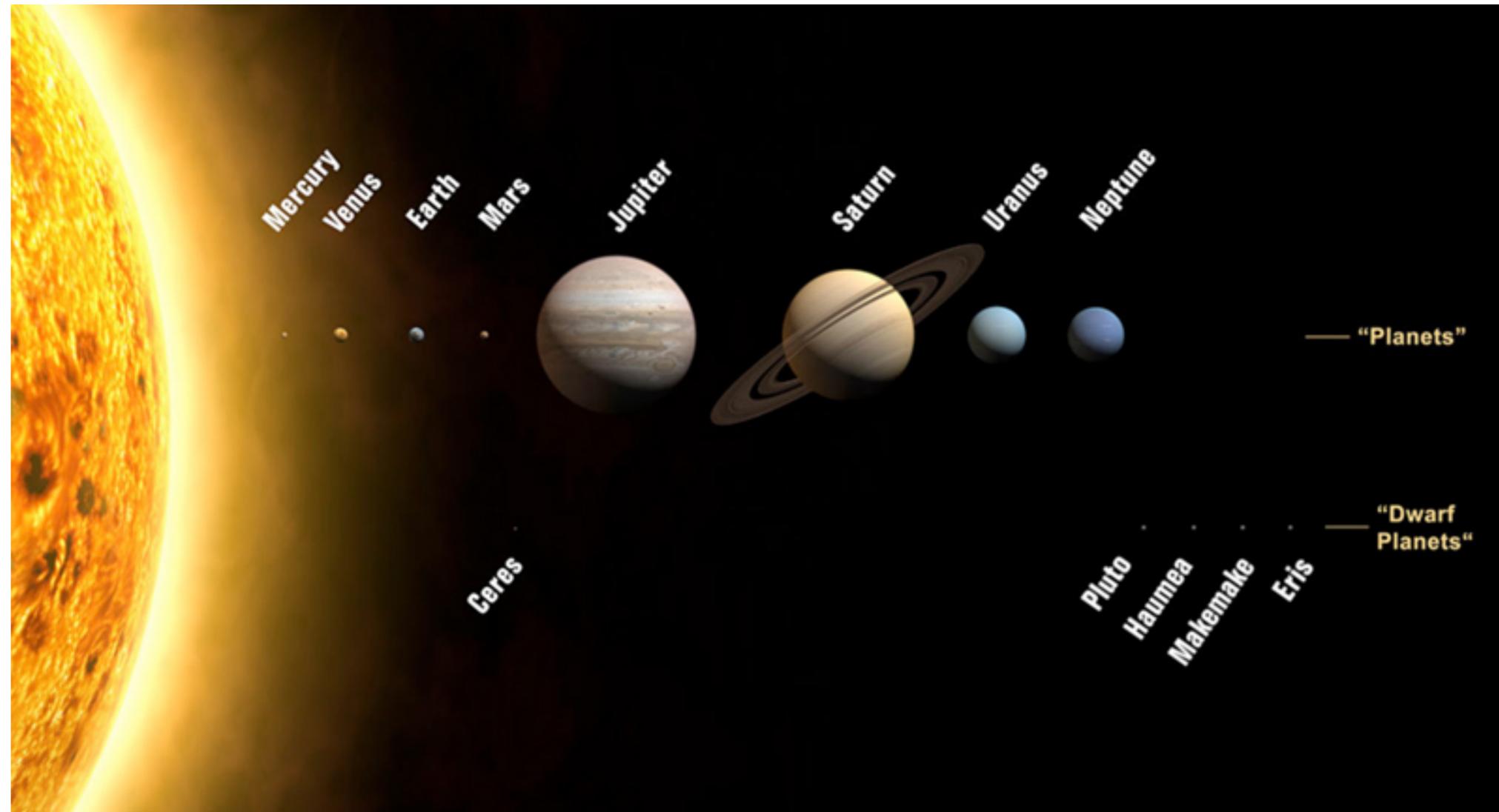
Direct Detection

- Direct detection of something (like a planet) involves directly detecting its light

- Direct imaging (taking an image where the planet is resolved from the host star) is a direct detection method

- Planets are faint and stars are bright, so this is hard

  - First direct detection of an exoplanet orbiting a brown dwarf: 2003

  - First direct detection of an exoplanet orbiting a star: 2008

2009-08-01   20 au
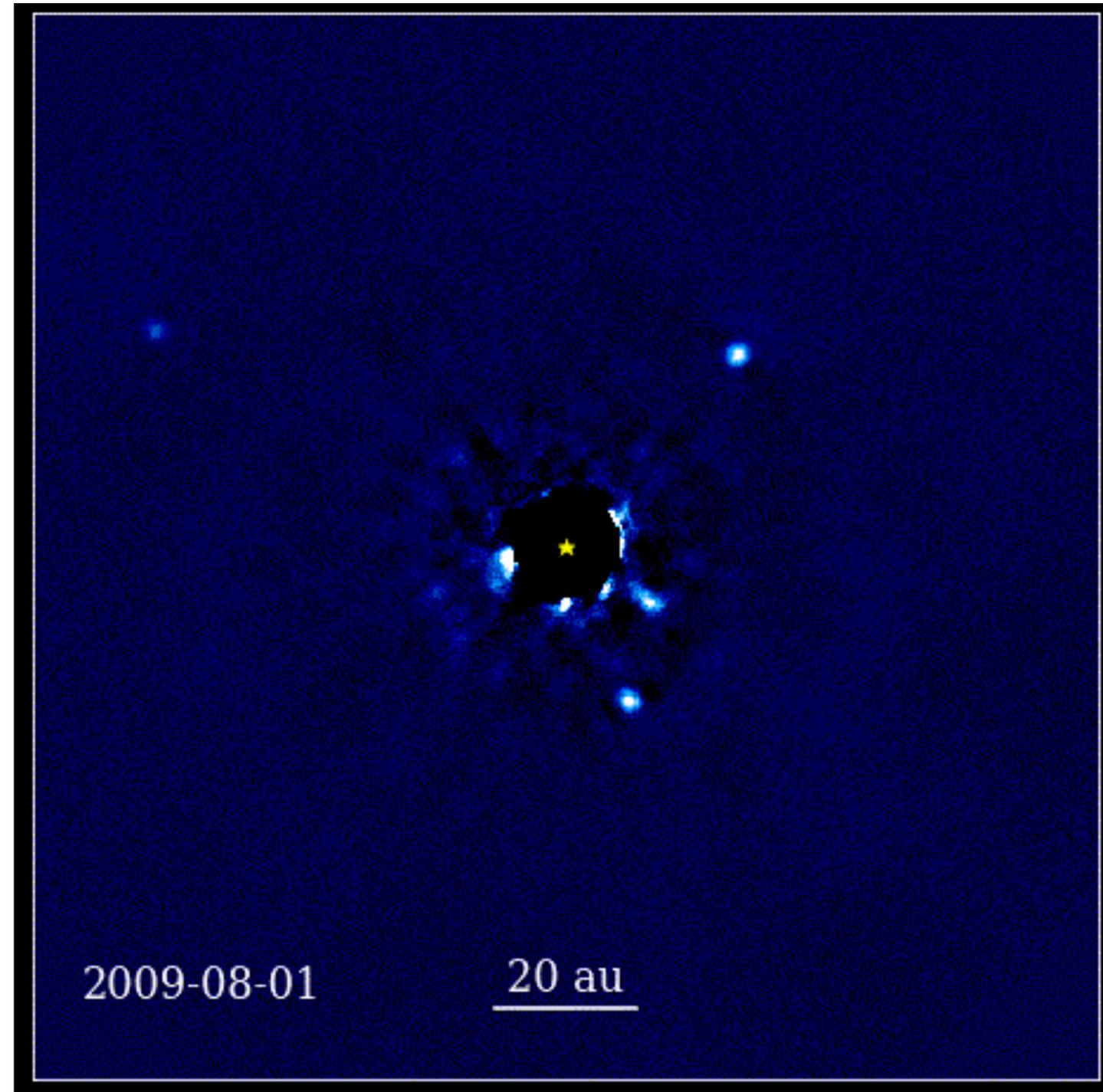
Movie from Jason Wang and Christian Marois

Indirect Detection

- For indirect detection, we infer the planet's presence:

  - from its gravitational influence

    - Gravity moves the host star, moves other planets in the system, bends light

  - from it blocking out the star's light

    - If the planet's orbit passes in a line between its host star and Earth, we see the star get fainter
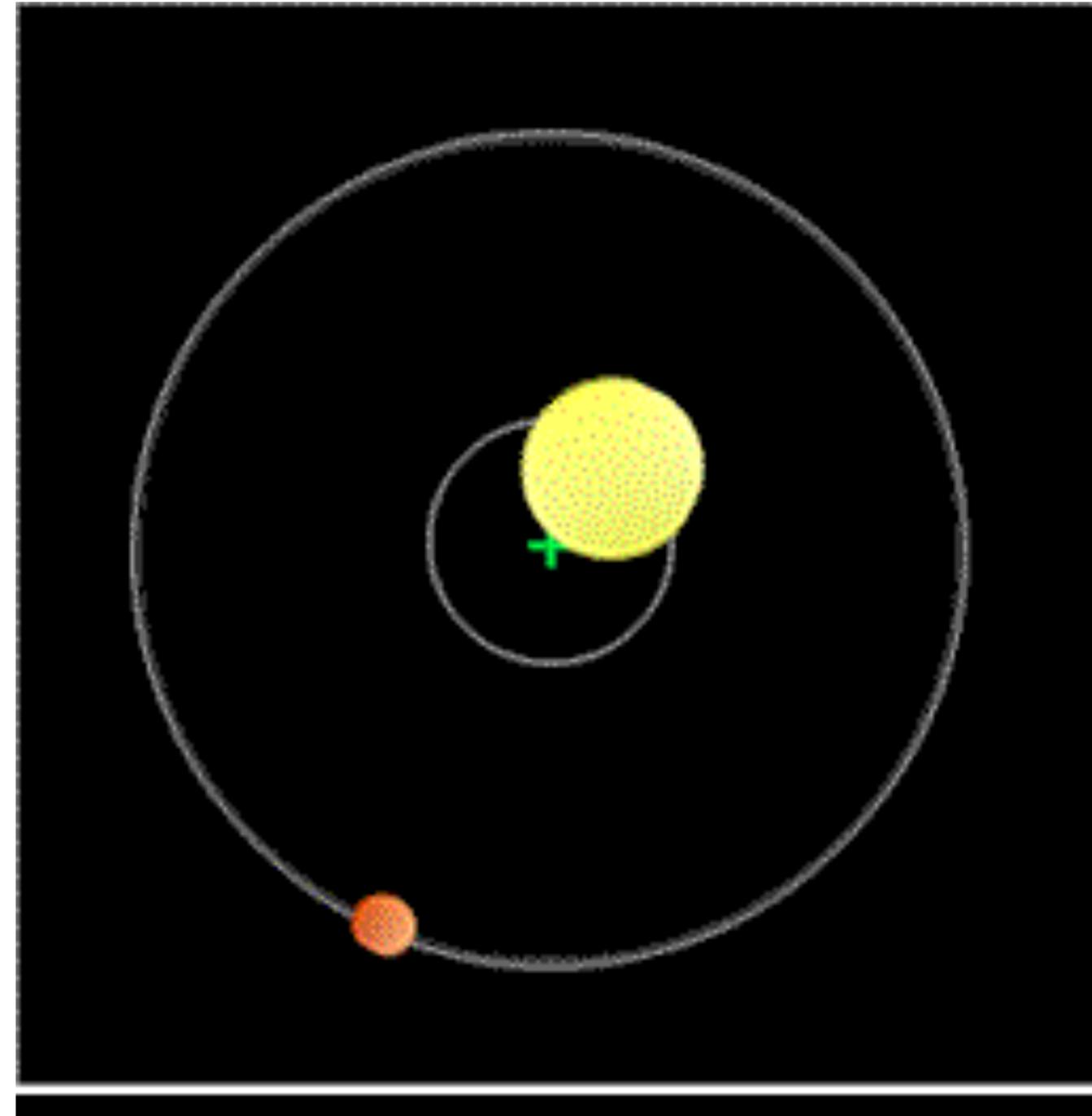
Indirect Detection

- First indirect detection of an exoplanet around a pulsar was in 1992

- First unambiguous detection of an exoplanet around a Sun-like star was in 1995
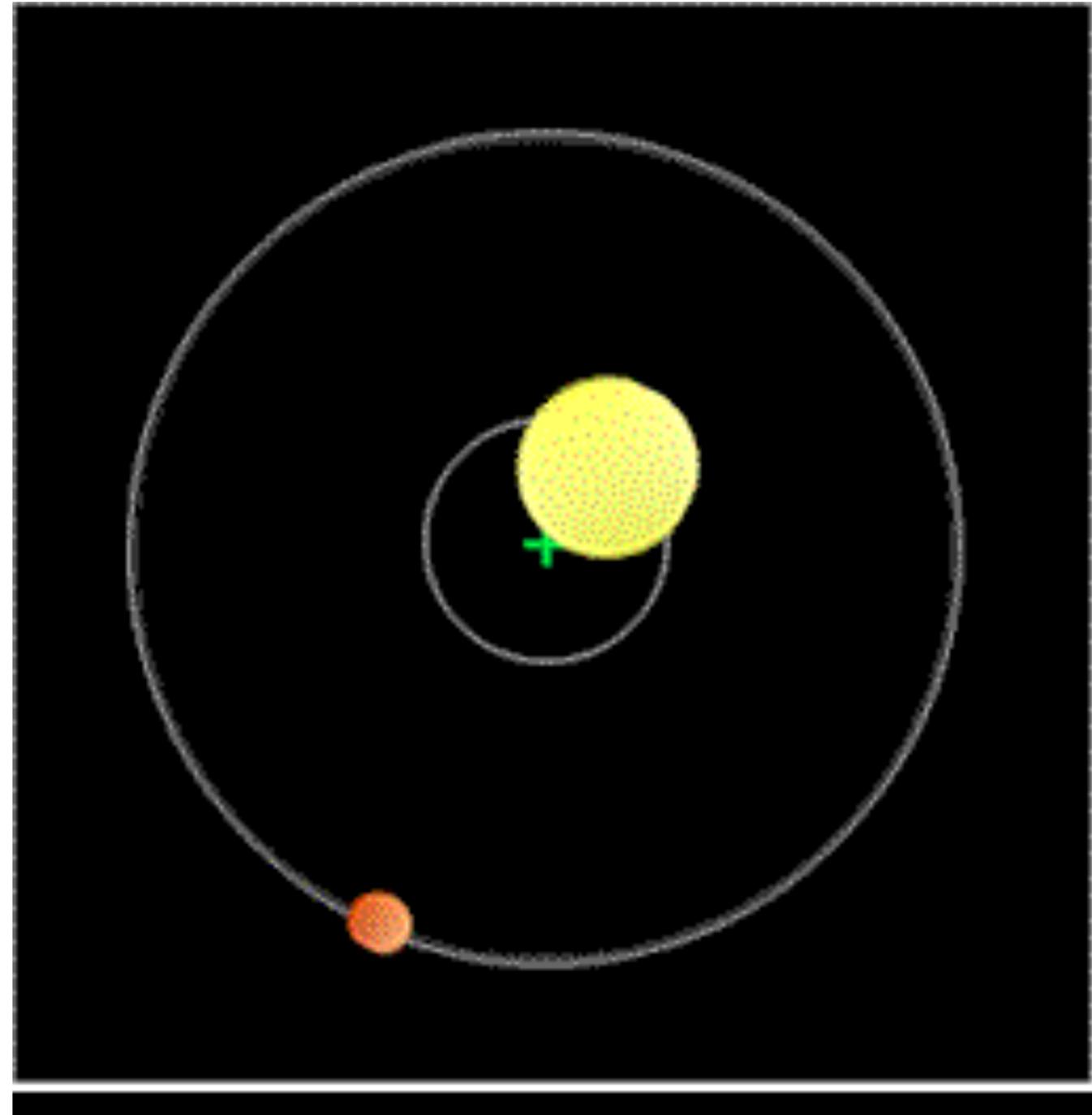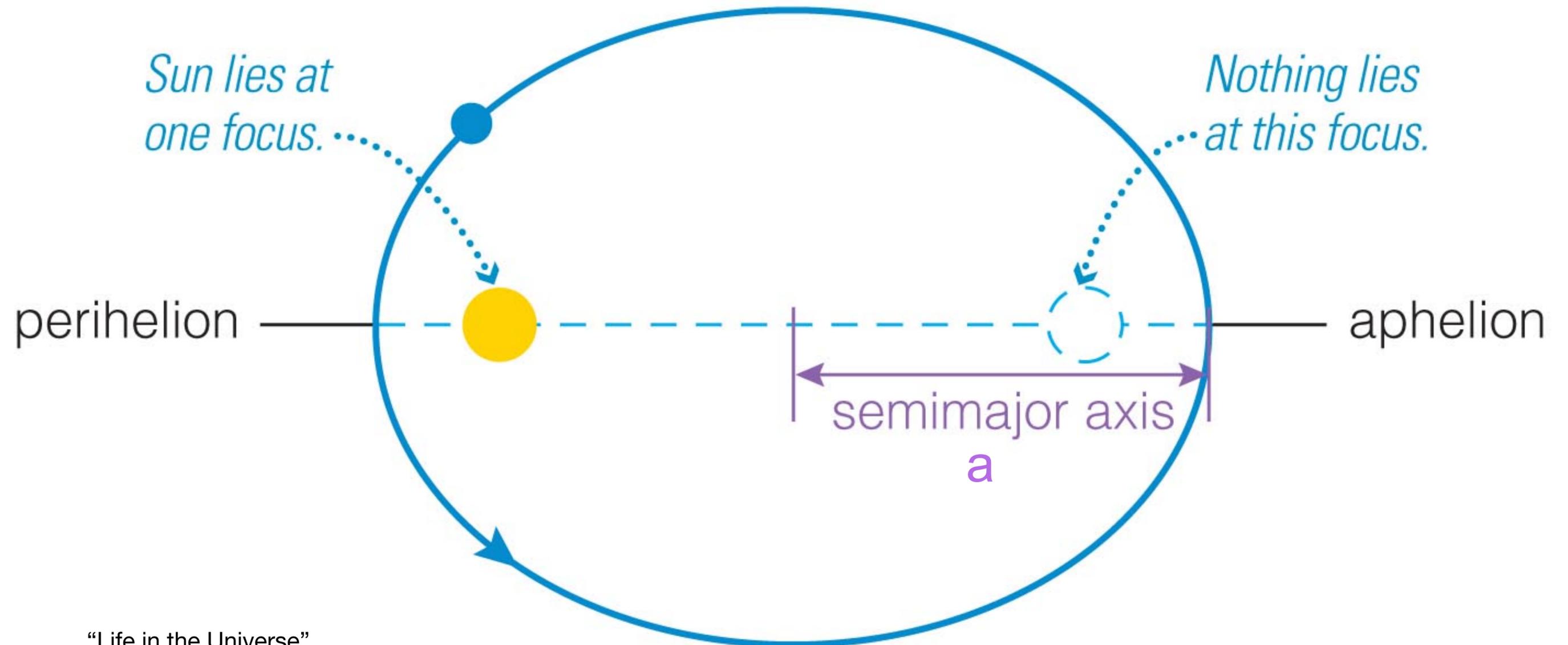
Break

Kepler's First Law

- The orbit of each planet around the Sun is an ellipse with the Sun at one focus.

Sun lies at one focus.

Nothing lies at this focus.

perihelion

aphelion

semimajor axis

a

"Life in the Universe"

Eccentricity

- Eccentricity (e) goes from 0 (circular orbits) to 1 (unbound orbit: a parabola)

- Closest approach, perihelion, is given by perihelion = (1-e) * a

- Furthest approach, aphelion = (1+e) * a

- -helion — Sun

- -gee — Earth

- -astron — Star

$e=0$ $e=0.5$ $e=0.75$ $e=0.9$
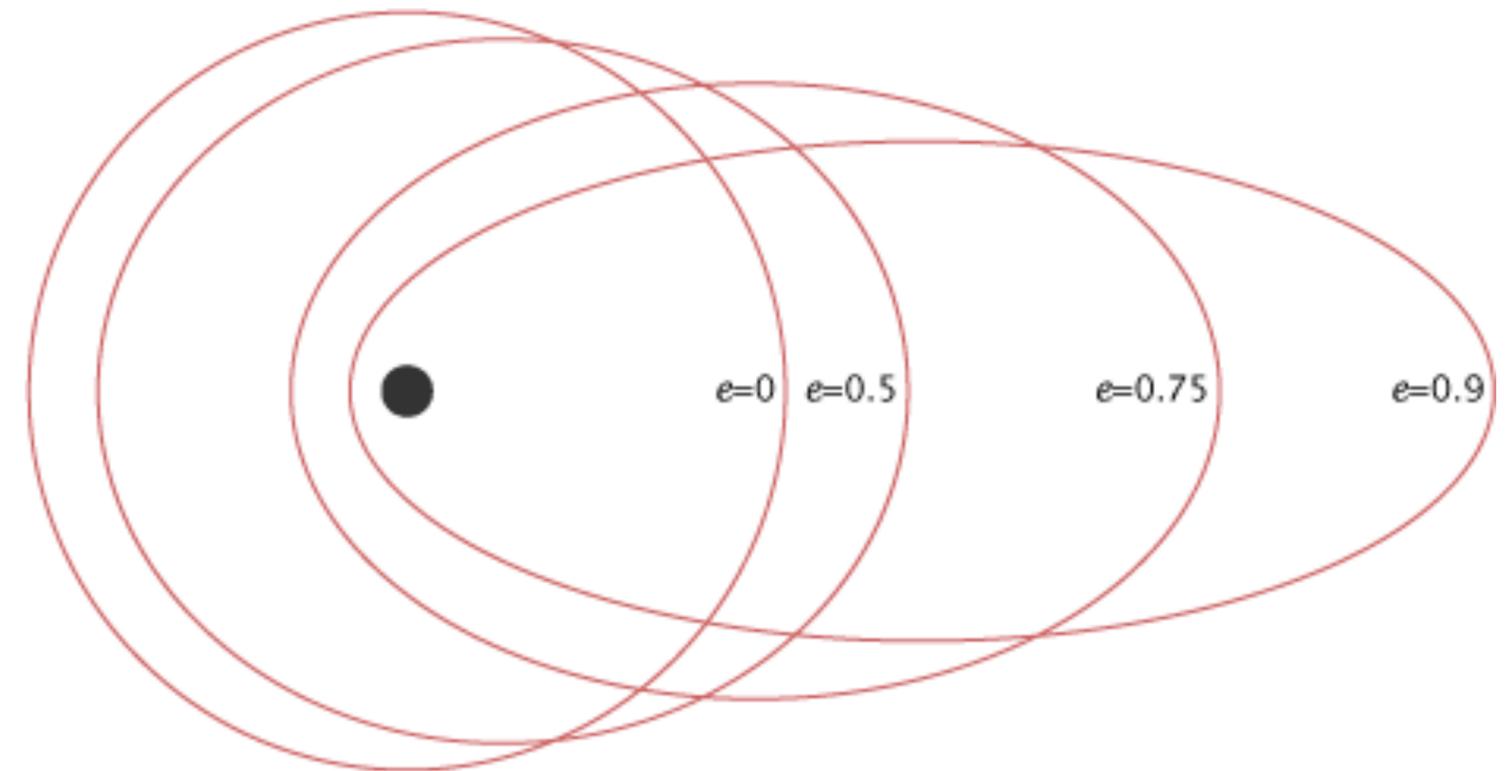
NASA

Kepler's Second Law

- As a planet moves around its orbit, it sweeps out equal areas in equal times.

- This means that a planet travels faster when it is nearer to the Sun and slower when it is farther from the Sun.

- Angular momentum (m * v * r) is conserved.

Near perihelion, in any particular amount of time (such as 30 days) a planet sweeps out an area that is short but wide.

Near aphelion, in the same amount of time a planet sweeps out an area that is long but narrow.

perihelion

aphelion

"Life in the Universe"
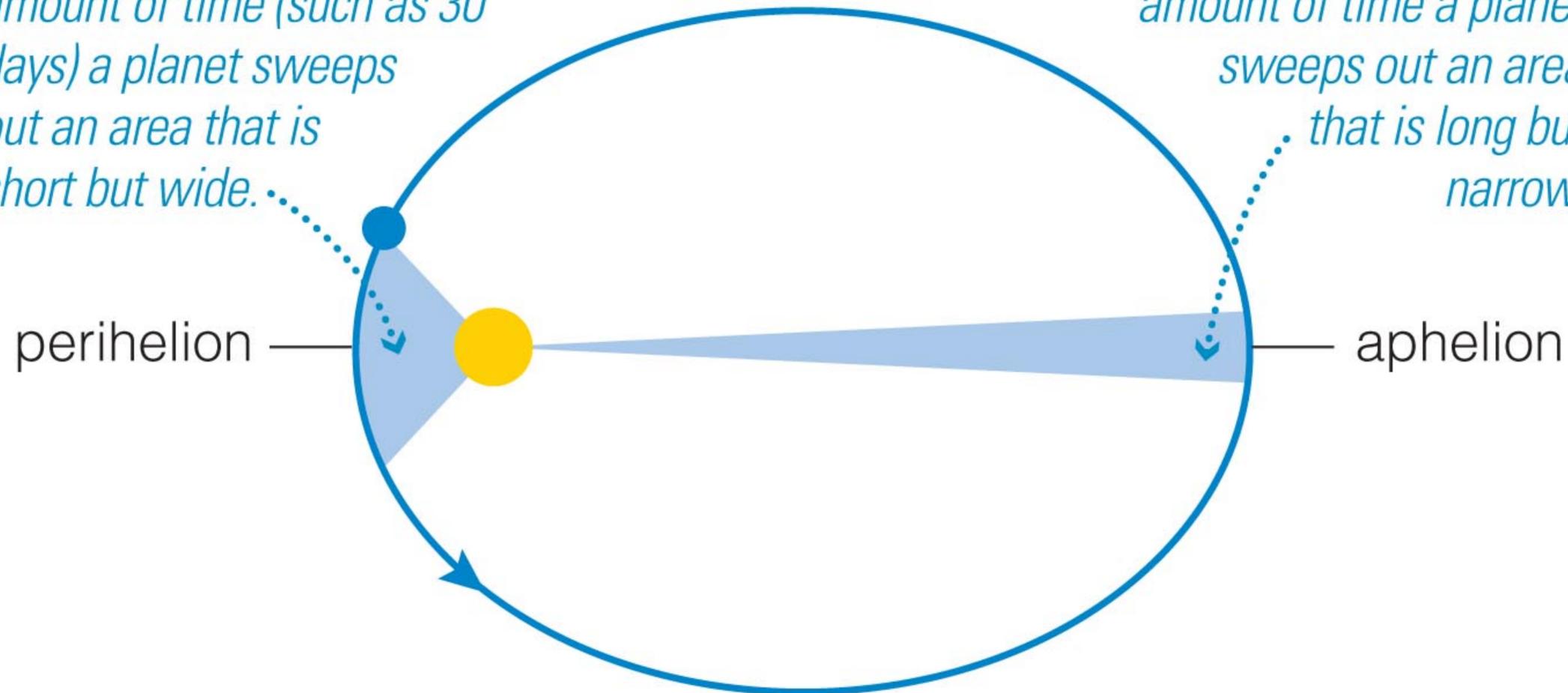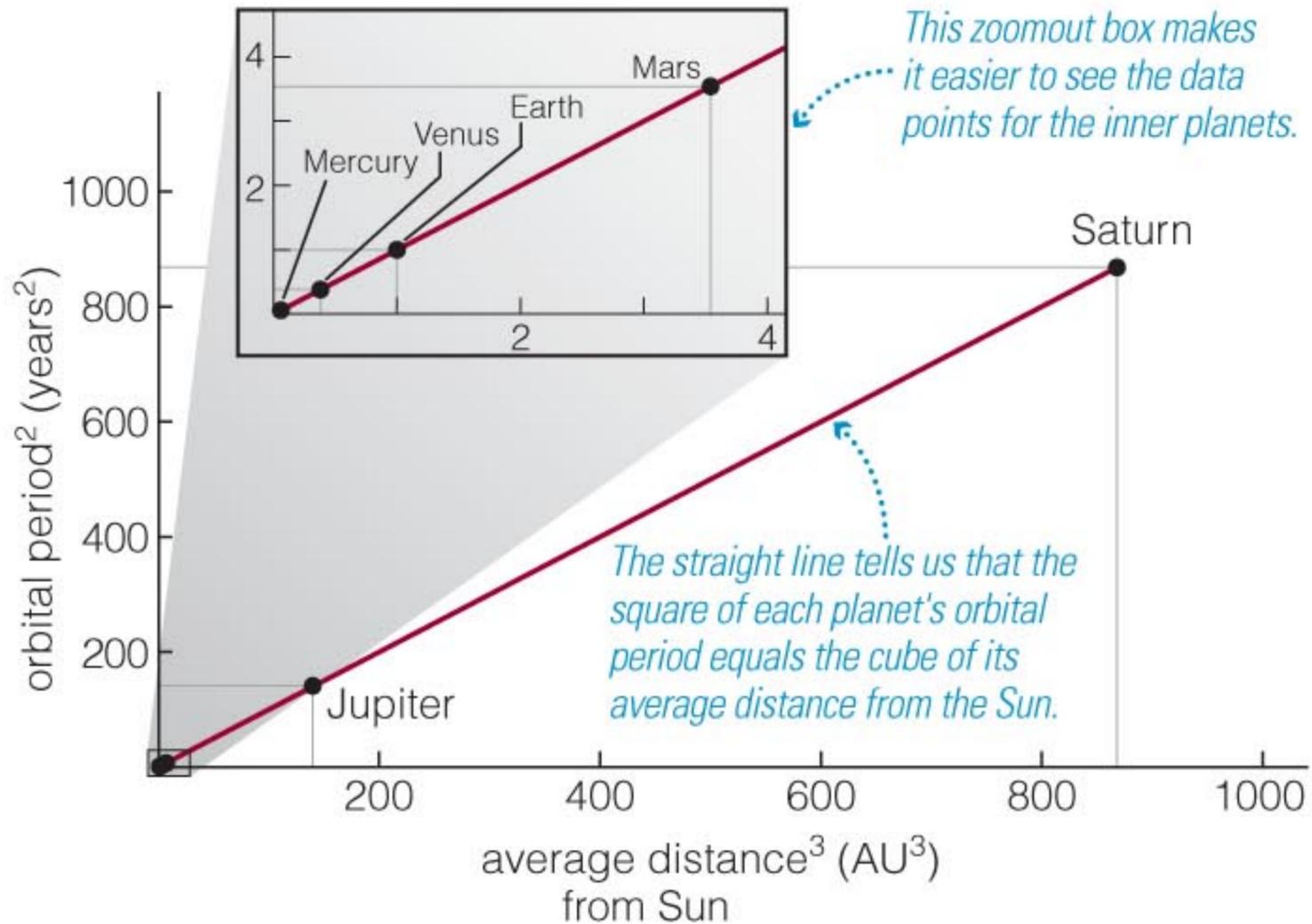
Kepler's Third Law

a This graph shows that Kepler's third law ($p^2 = a^3$) holds true; the graph shows only the planets known in Kepler's time.
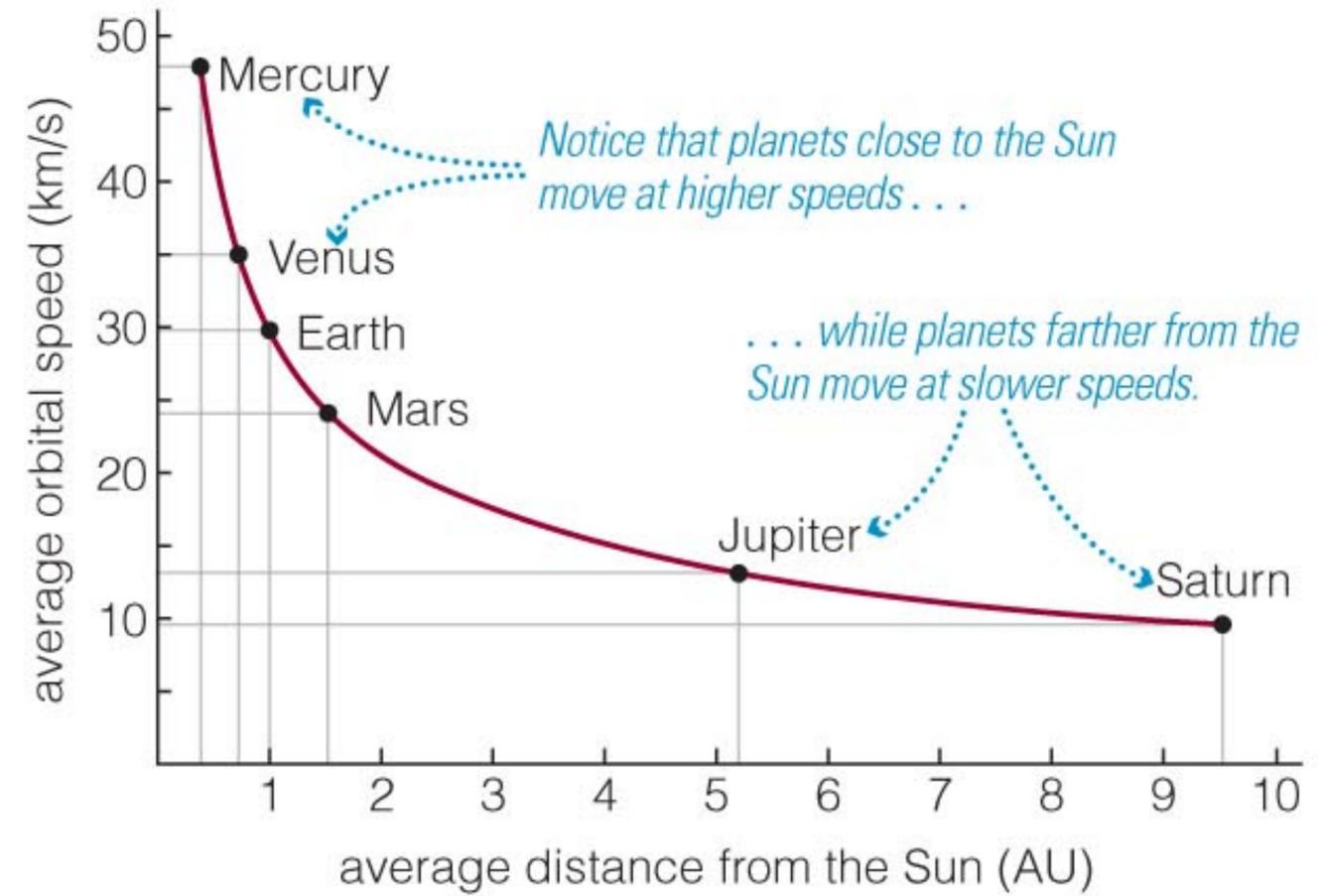
b This graph, based on Kepler's third law and modern values of planetary distances, shows that more distant planets orbit the Sun more slowly.

Newton's Version of Kepler's Third Law

- Newtons' version of Kepler's third law, dumb units:
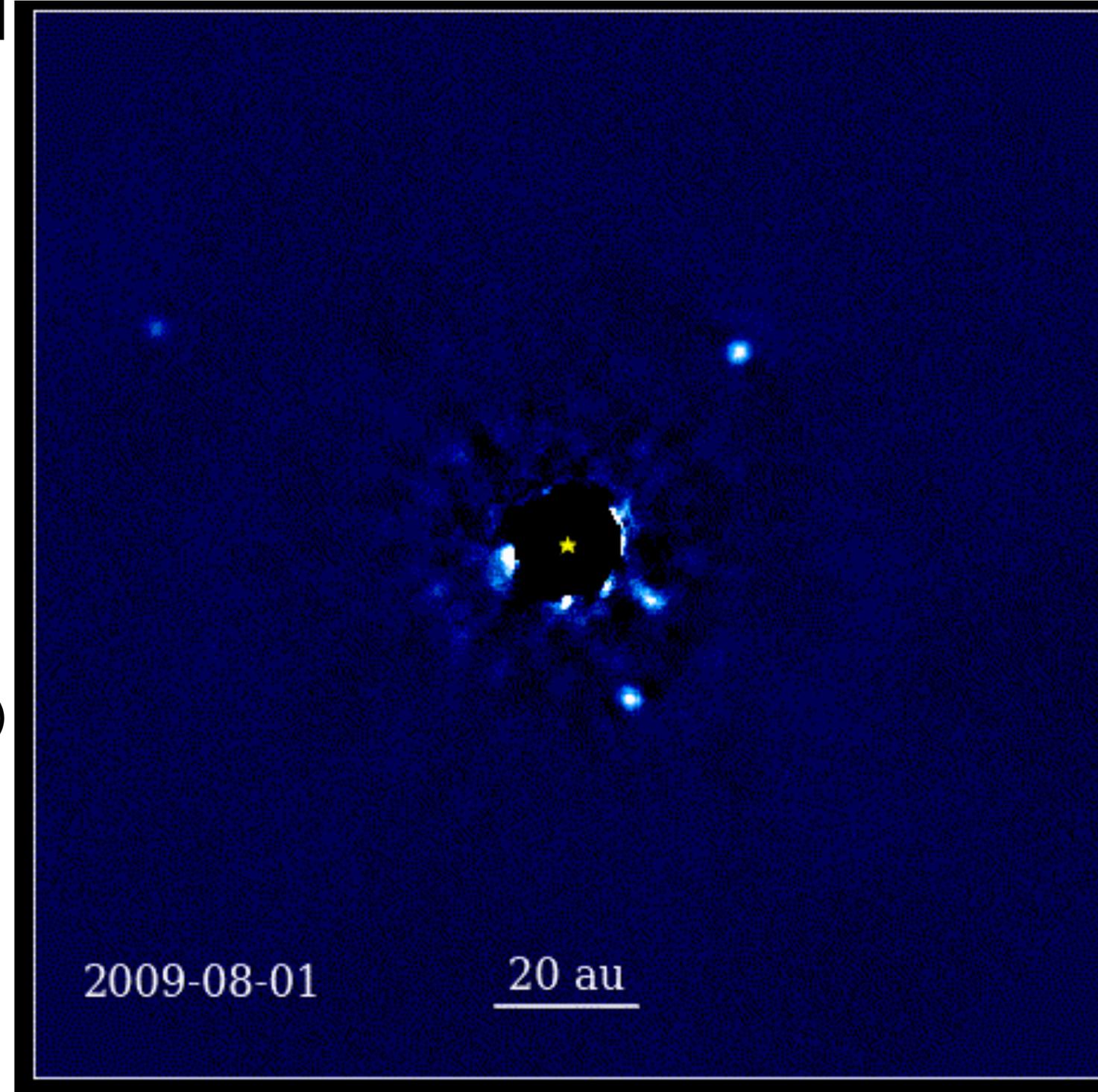
$$P^2 = \frac{4\pi^2 a^3}{GM_{total}}$$

- Newton's version of Kepler's third law, smarter units:

$$P^2 = \frac{a^3}{M_{total}}$$

(P in years, a in AU, M_{total} in solar masses)

2009-08-01   20 au

Movie from Jason Wang and Christian Marois

Center of Mass
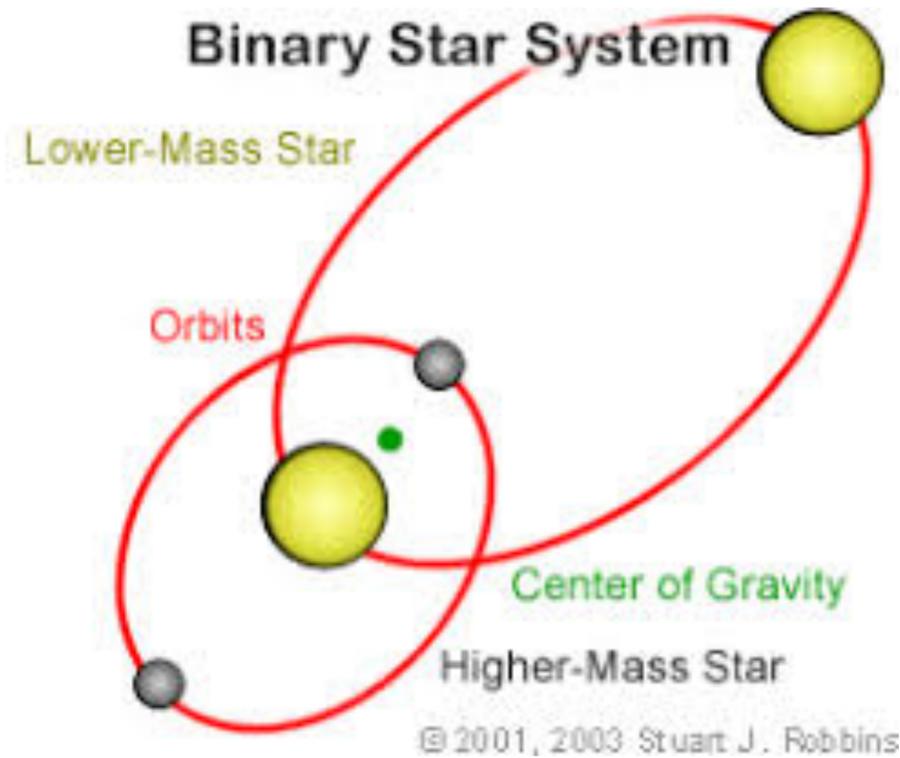
- Really, both objects in an orbit move around their common center of mass

- The two ellipses have different semi-major axes, but the center of mass is at a focus of each

$$a_1 M_1 = a_2 M_2$$

- The two orbits have the same period

$$P^2 = \frac{(a_1 + a_2)^3}{M_1 + M_2}$$

Binary Star System

Lower-Mass Star

Orbits

Center of Gravity

Higher-Mass Star

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Order of Magnitude: Center of Mass

- $a_1 M_1 = a_2 M_2$

$$P^2 = \frac{(a_1 + a_2)^3}{M_1 + M_2}$$

- (1) What is the semi-major axis of the Sun's orbit around the Sun/Jupiter center of mass, in AU? In solar radii?

- (2) What is the semi-major axis of the Sun's orbit around the Sun/Earth center of mass, in AU? In solar radii?
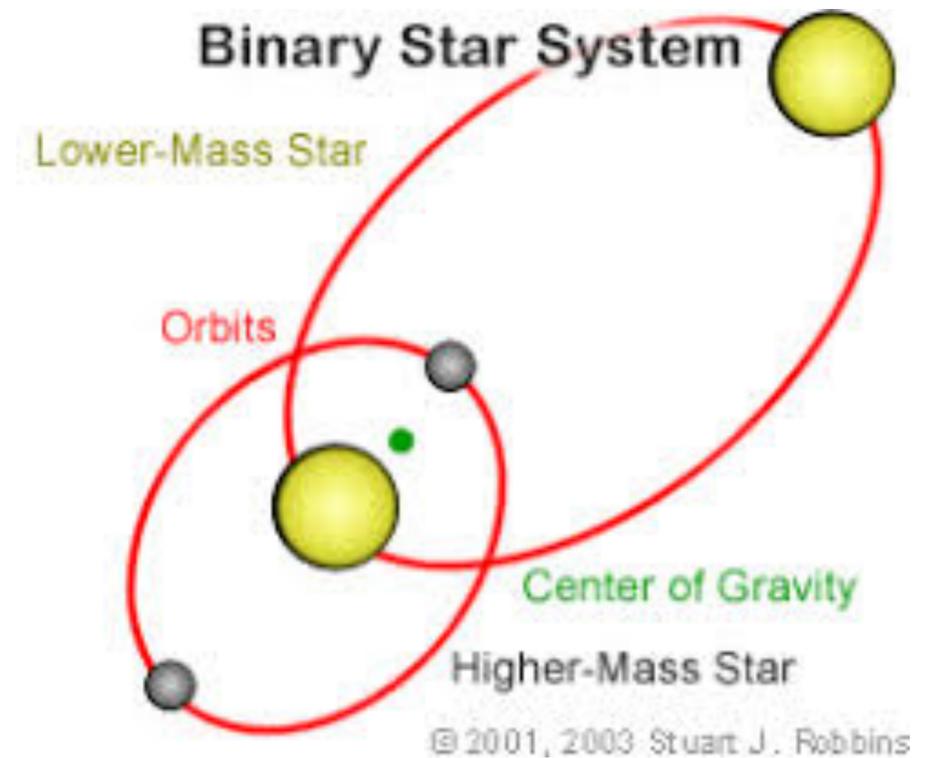
Order of Magnitude: Center of Mass

- $a_1 M_1 = a_2 M_2$

$$P^2 = \frac{(a_1 + a_2)^3}{M_1 + M_2}$$

- (1) What is the semi-major axis of the Sun's orbit around the Sun/Jupiter center of mass, in AU? In solar radii?

- Jupiter has a semi-major axis of 5.2, and is 1000 times less massive than the Sun. Given that, we can assume:

- $a_{tot} = a_1 + a_2 \approx a_2 = 5.2AU$

- Then we can solve for a_1:

$$a_1 = \frac{M_2}{M_1} a_2 = \frac{1}{1000}(5.2AU) = 5.2x10^{-3}AU$$

Order of Magnitude: Center of Mass

- Now we need to convert AU to solar radii. The Sun is 10x larger than Jupiter which is 10x larger than Earth. And Earth is 6000 km in radius, so:

$$R_\odot = 100x6000km = 6x10^5 km \frac{1AU}{1.5x10^8 km} = 4x10^{-3}AU$$

- Great, now we convert:

$$a_1 = 5.2x10^{-3}AU \frac{R_\odot}{4x10^{-3}AU} = 1R_\odot$$

- (2) What is the semi-major axis of the Sun's orbit around the Sun/Earth center of mass, in AU? In solar radii?

- Same procedure as above, but we just need to know that Earth is 300x less massive than Jupiter, and the semi-major axis is 1 AU for Earth's orbit around the Sun:

$$a_1 = \frac{M_2}{M_1}a_2 = \frac{1}{300x1000}(1AU) = 3x10^{-6}AU \qquad a_1 = 3x10^{-6}AU \frac{R_\odot}{4x10^{-3}AU} = 10^{-3}R_\odot$$
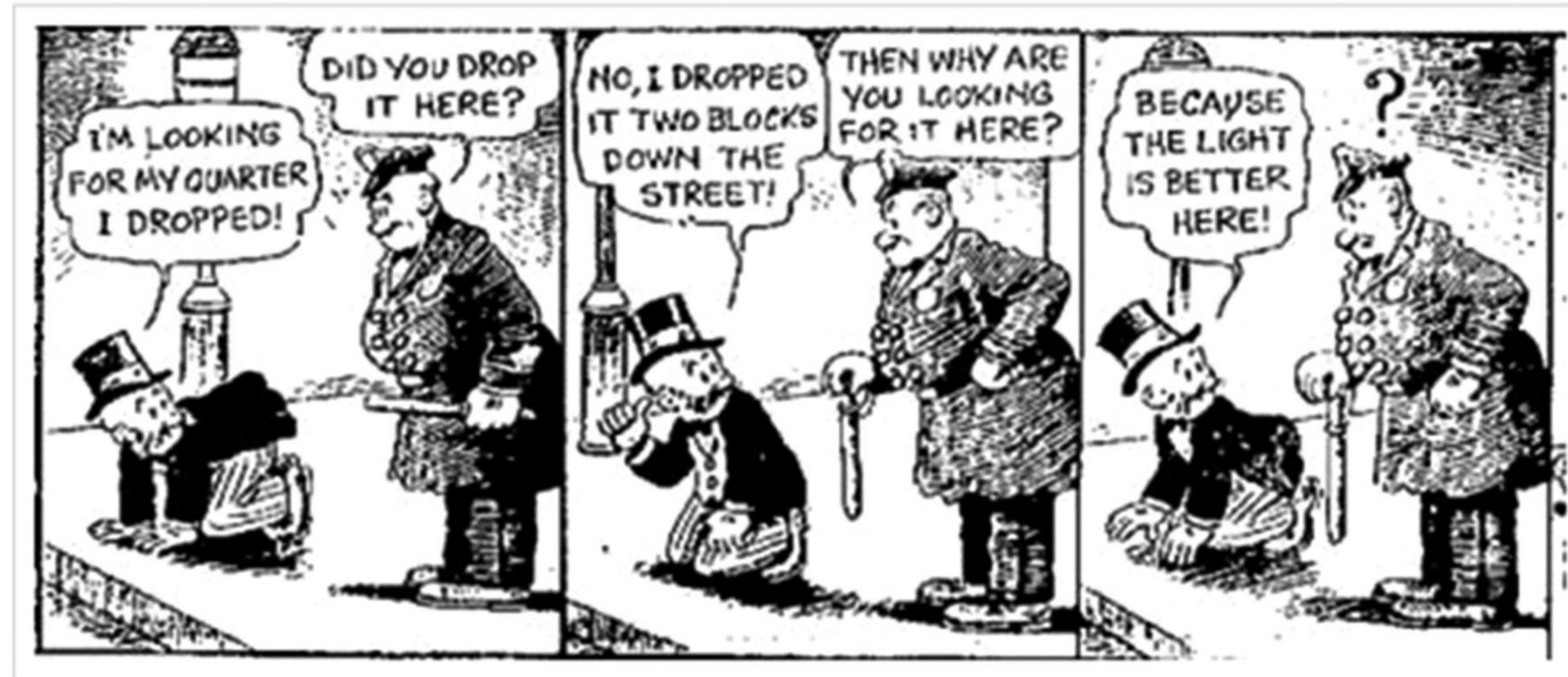
Exoplanet Demographics

- Thousands of exoplanets currently known

  - Most found with the transit and radial velocity method

- Type of planets found depends on sensitivity of detection method

- Transit and radial velocity method are both very good at finding large planets very close to their star
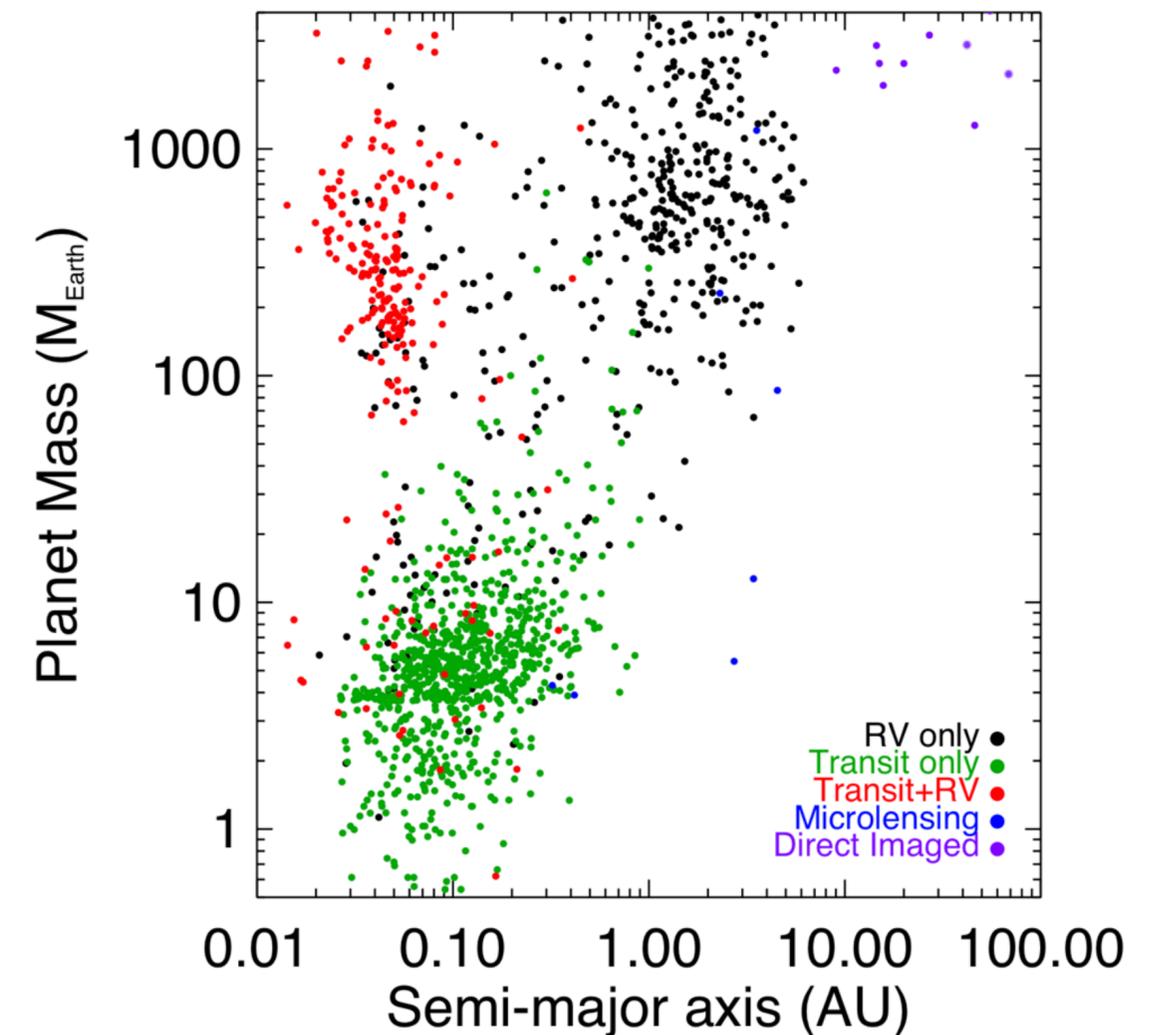
The Streetlight Effect

- We will find more examples of things that are easier to find than things that are harder to find

- For extrasolar planets: each technique has its own biases, and discoveries are dominated by the easiest-to-find exoplanets

- Improvements in technology allow us to be sensitive to types of exoplanets that were previously undetectable

Mutt and Jeff/Florence Morning News

Exoplanet Demographics

- The most common type of planet we currently know about isn't necessarily the most common type of planet

- Observational biases of each technique shape the population of currently known exoplanets
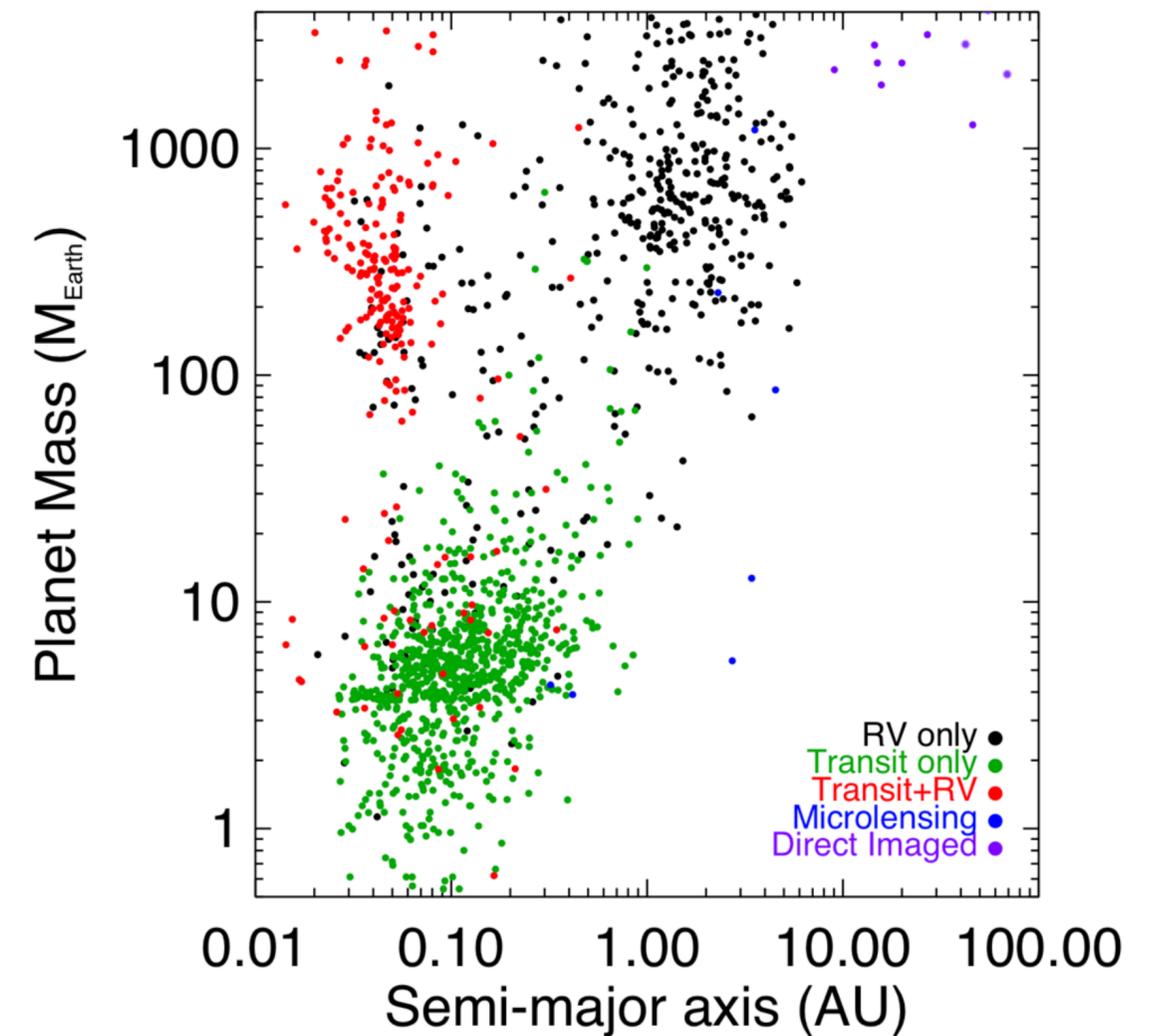
Exoplanet Demographics

- Solar System analogs are still difficult to find with current search techniques

  - Jupiter analogs have been found in the past 2 decades

  - It will take longer to find analogs of other solar system planets
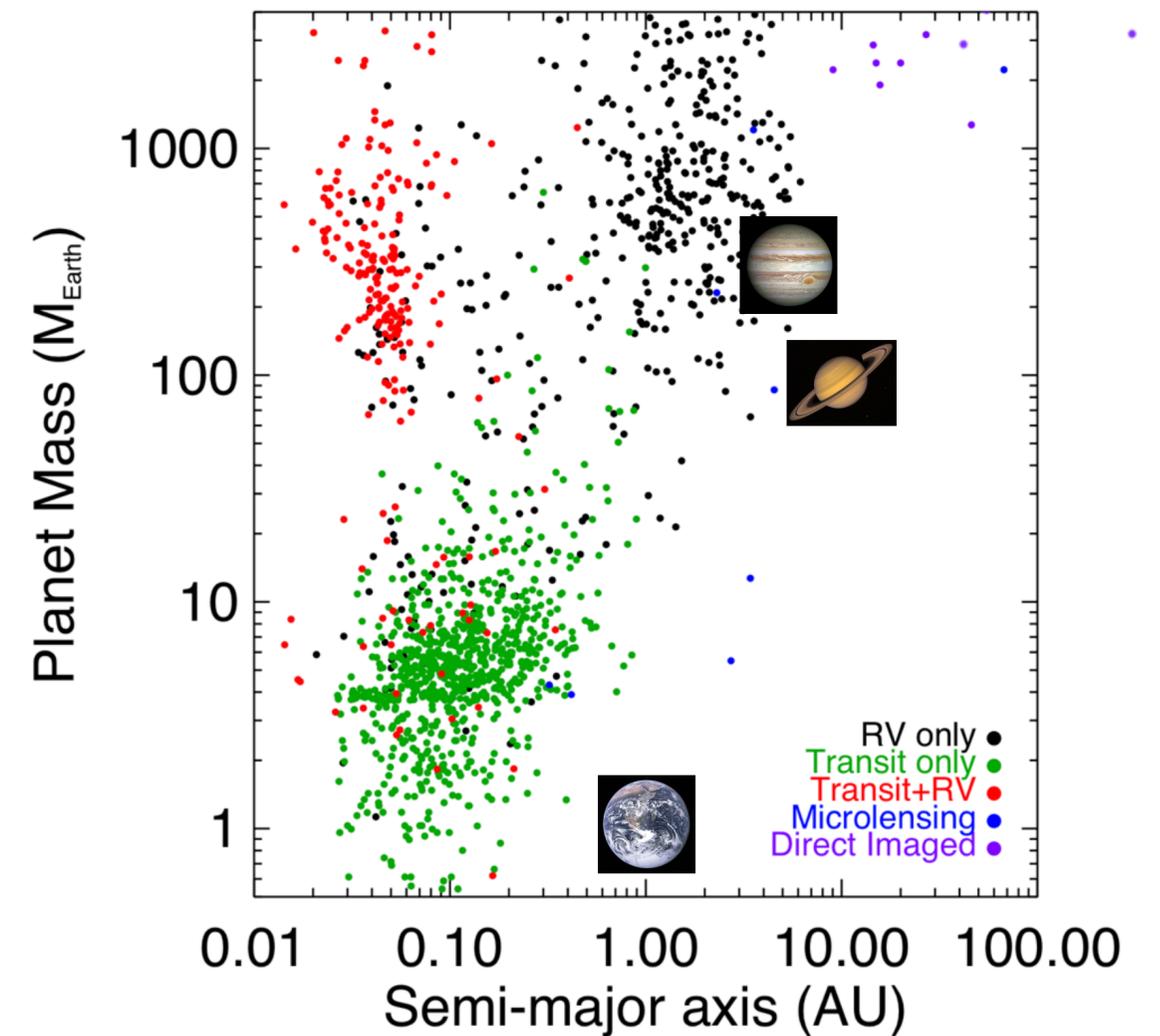
Pulsar Planets

- In 1992, three small planetary-mass objects (a few times the mass of Earth) were indirectly detected orbiting the pulsar PSR1257+12

- Detected via the "Pulsar Timing method"


Wolszczan & Frail 2002
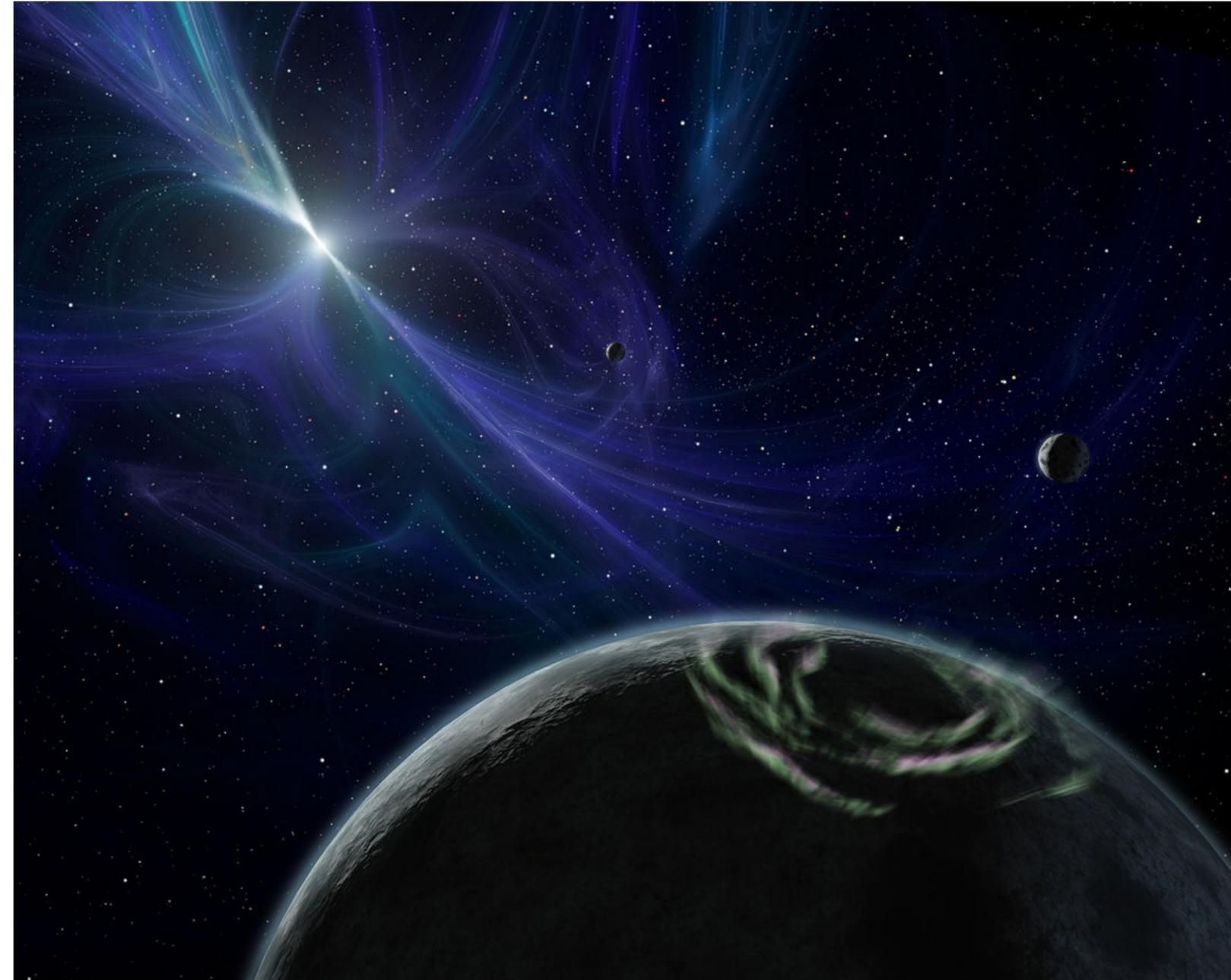
Pulsar Planets

- Pulsars give off very regular radio signals as they rotate

- As something orbits the pulsar, the pulsar gets closer to and further away from Earth (by a few light milliseconds)

- The pulses from the pulsar arrive a few milliseconds early, or late, as the object orbits

Pulsar Planets

- A few other pulsars also found to have planetary-mass companions

- Do these count as planets?

  - Whatever they are, they survived a supernova

  - Could have been larger objects that lost mass during the supernova

  - Could have been formed out of stellar material during post-main sequence evolution
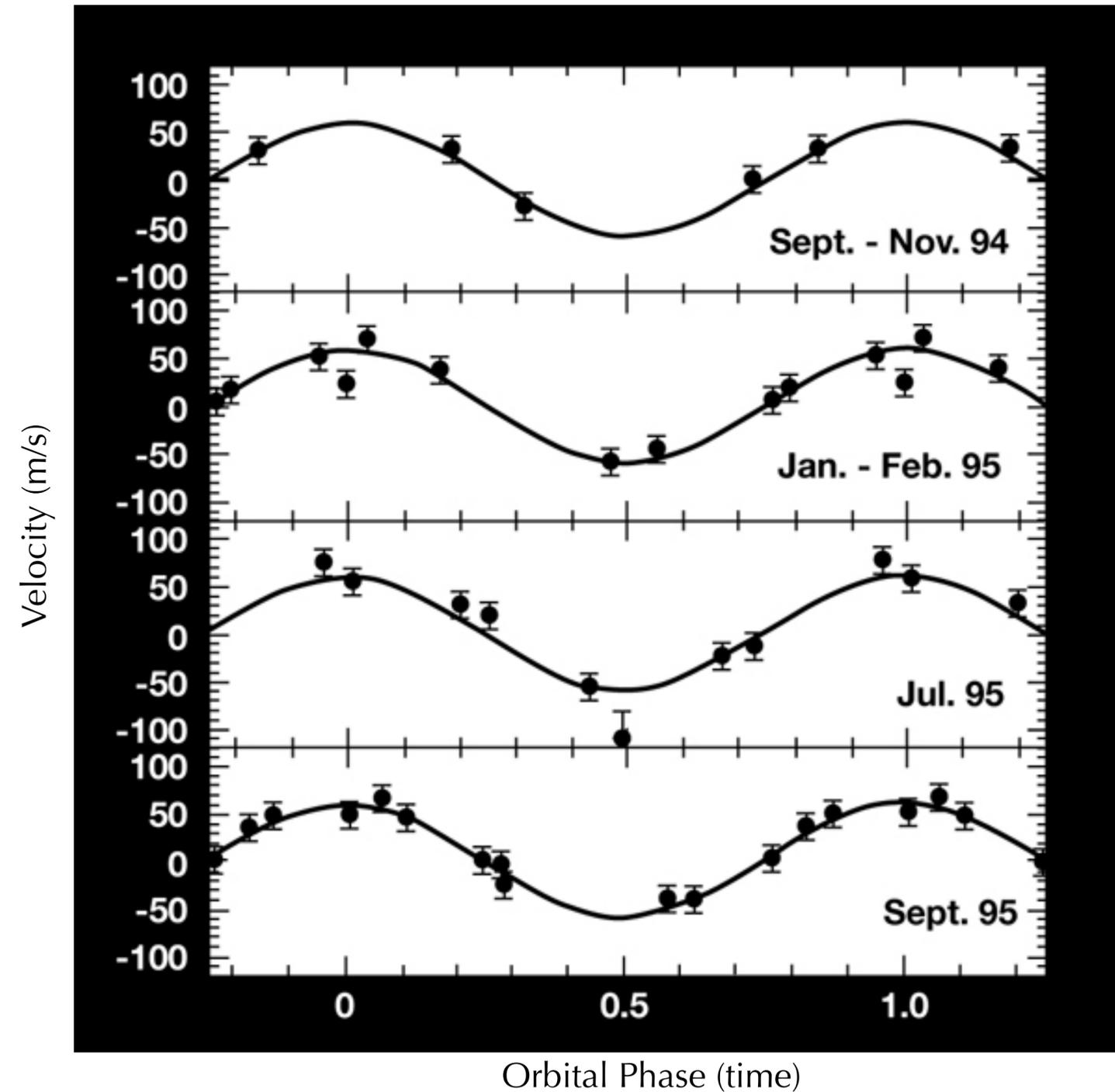

Wolszczan & Frail 2002
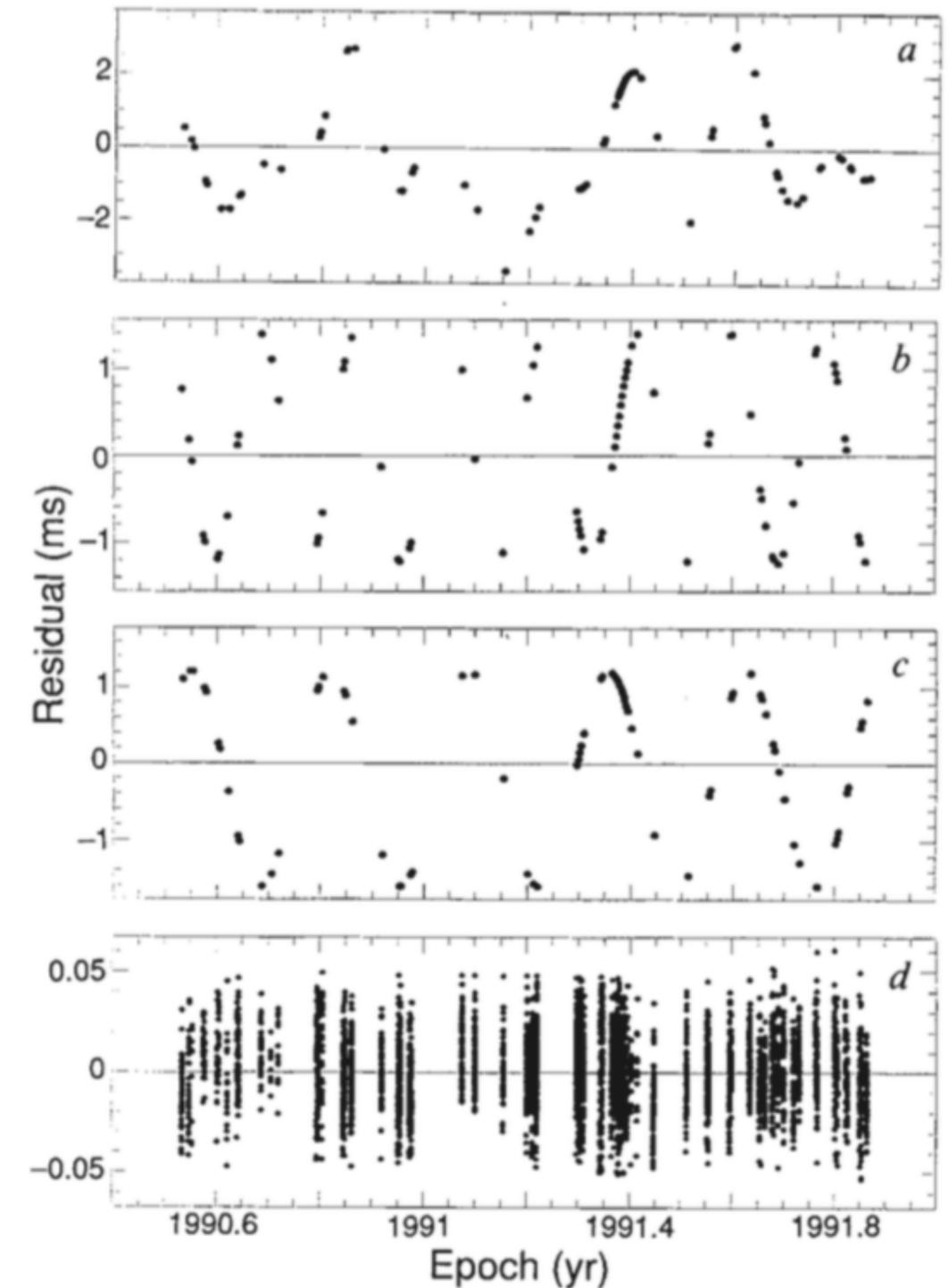
The Radial Velocity Method

- A star with a planet will orbit the common center of mass of the star/ planet system

- Some component (most of the time) of the star's motion will be along the line-of-sight

- That radial velocity (RV) can be detected by a shift in the star's absorption lines over an orbit

OASA
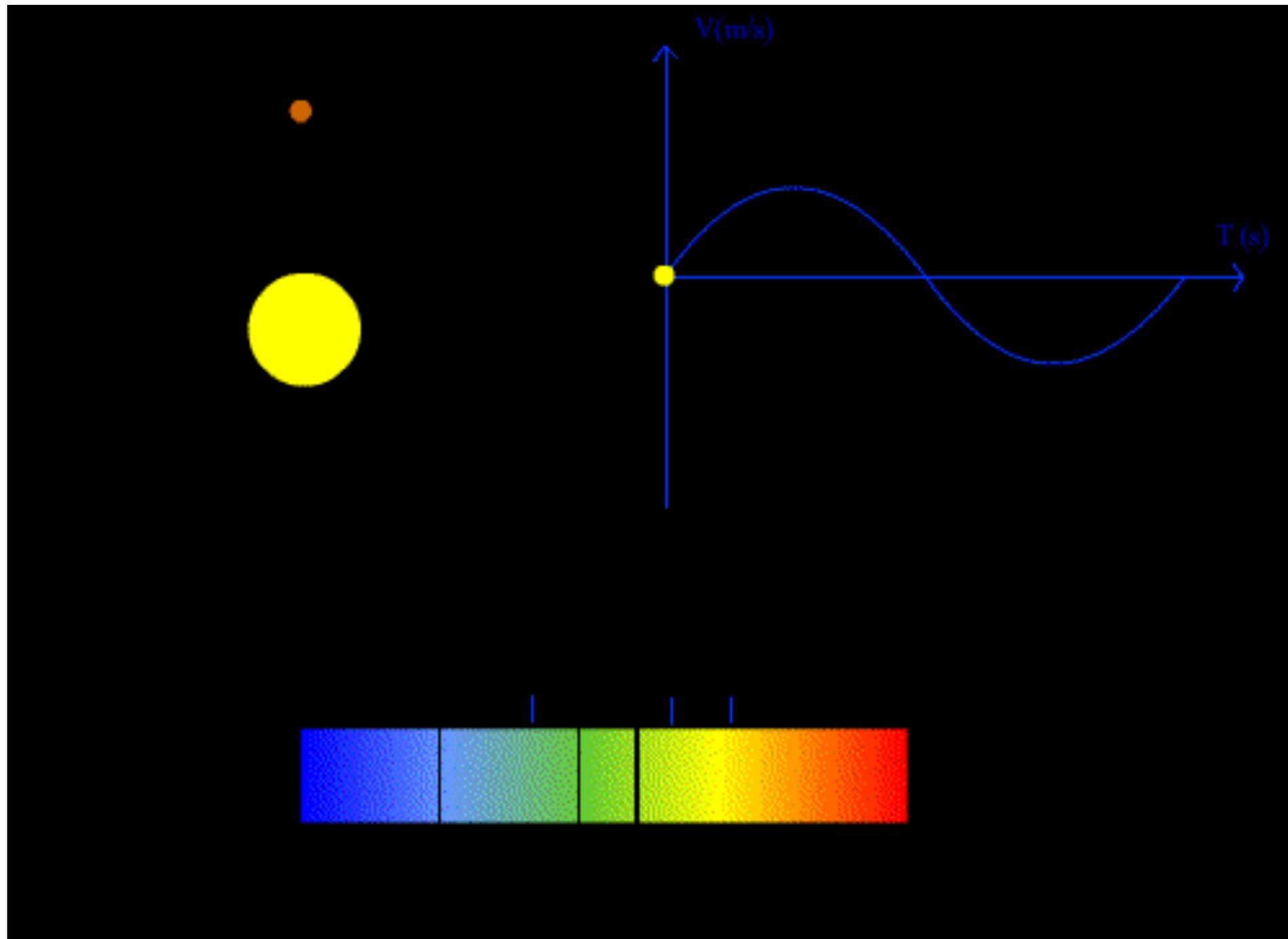
The Radial Velocity Method

- The first exoplanets found by this method were "Hot Jupiters"

  - Jupiter-mass (and larger)

  - Close to their star (much closer than Mercury is to the Sun): orbital period of a few days

- These objects produce an RV signal in their star of ~50 m/s

  - Fastest human running speed is about 10 m/s

Velocity (m/s)

Sept. - Nov. 94

Jan. - Feb. 95

Jul. 95

Sept. 95

Orbital Phase (time)

Mayor & Queloz 1995

The Radial Velocity Method

- Requires very high RV precision: a few m/s (human walking speed)

- Spectrographs typically "drift" over the night by a few km/s

  - Thermal expansion of spectrograph, and air changing temperature (and so index of refraction)

Anne Peck
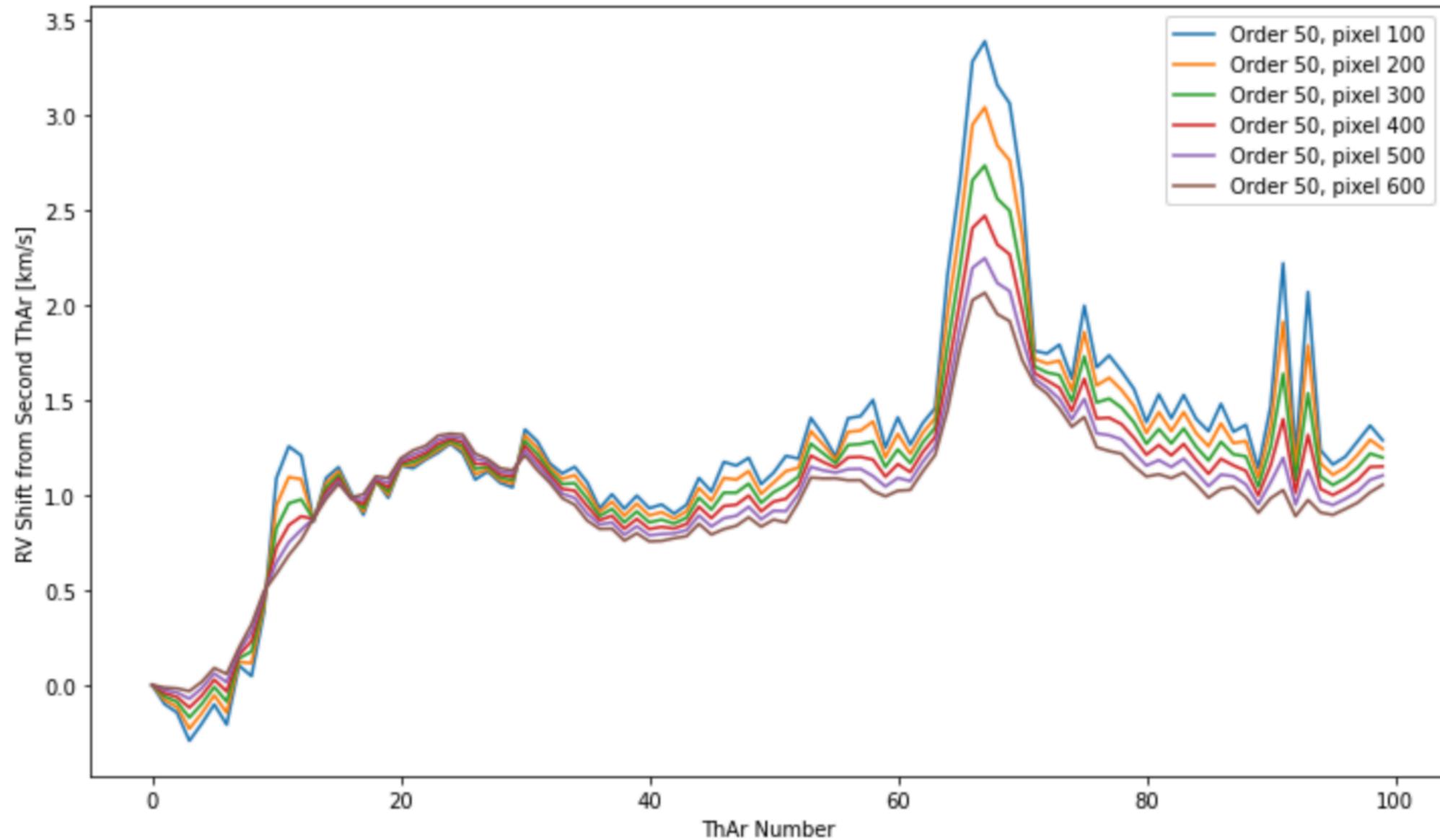
The Radial Velocity Method

- Greatly improve RV precision by simultaneously observing a wavelength standard while you observe your star

  - Observe ThAr calibration lamp simultaneously

  - Put an "iodine cell" in the path, so starlight passes through gaseous iodine

  - Use molecular absorption line in Earth's atmosphere in your star spectrum

- Modern precision is about 1 m/s on the least-active stars

Anne Peck
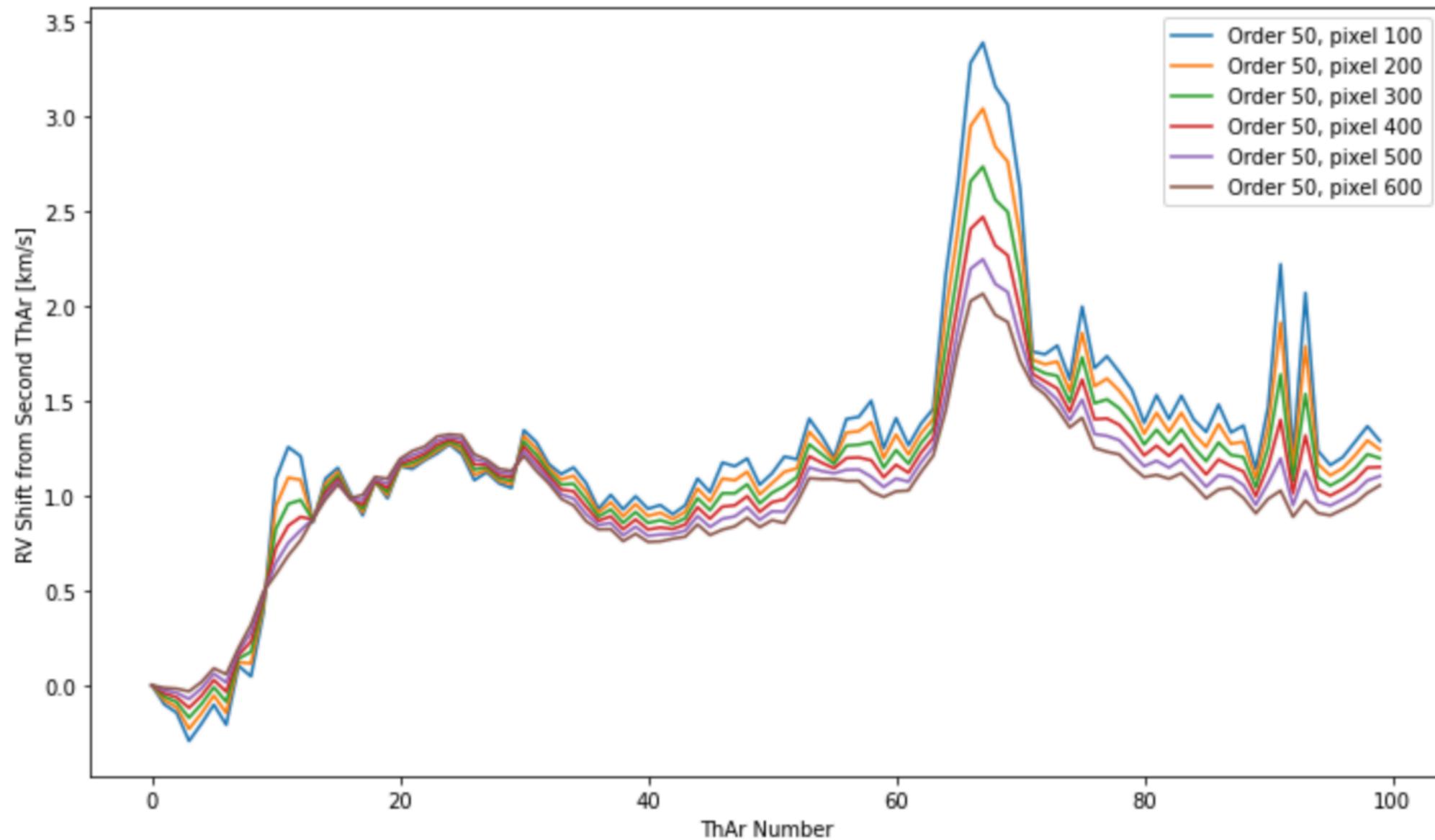
For next time

- Reading: Planetary Science, 12.1, 12.2.1-12.2.2