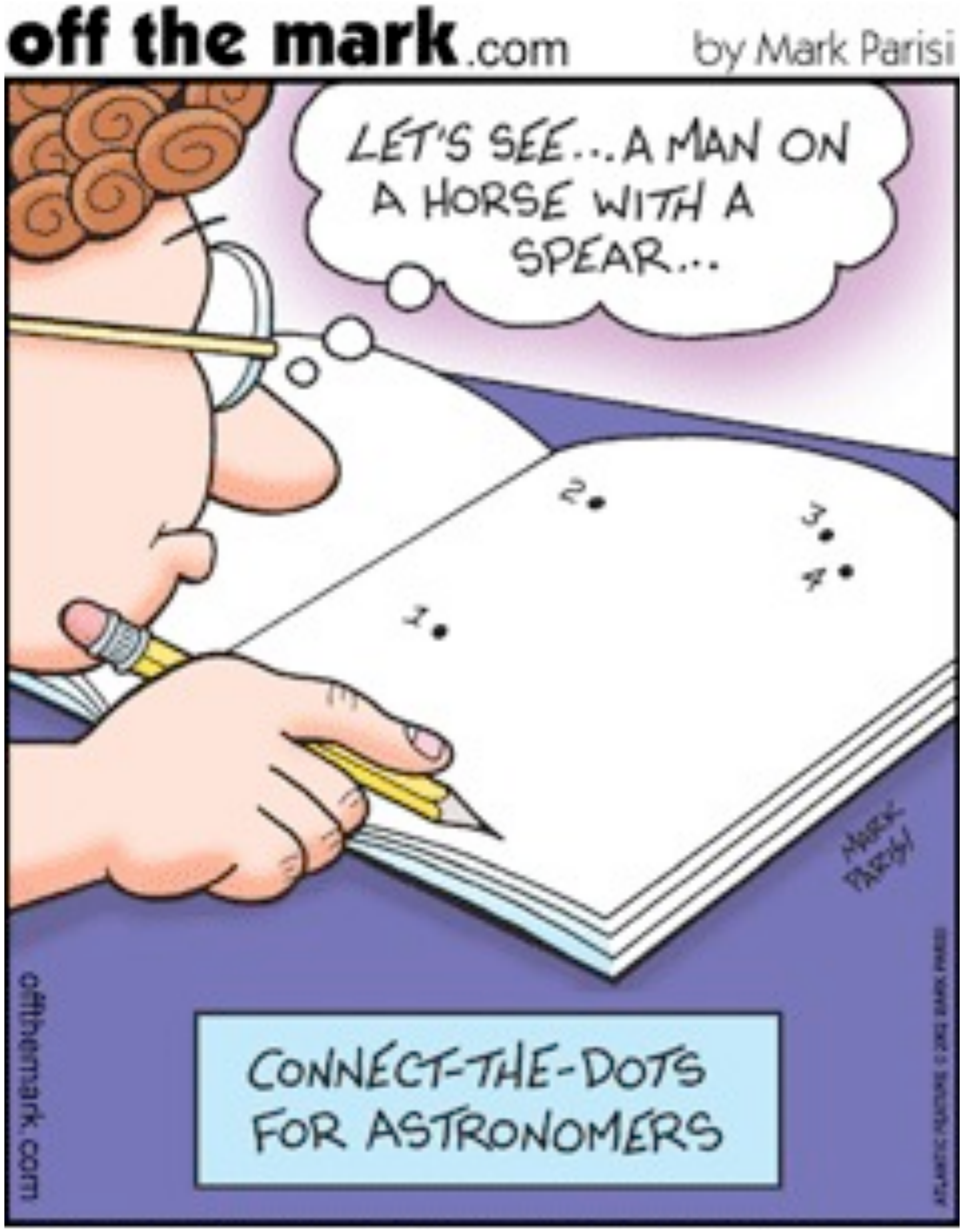
ASTR 150

- Planetarium Shows begin Sept 9th
  - Info on course website
- Register your iClicker!
- Last time: The Night Sky
- Today: Motion and Gravity
  - Hang on tight! Most math all semester-- get it over with right away



I'm your Moon – Jonathan Coulton

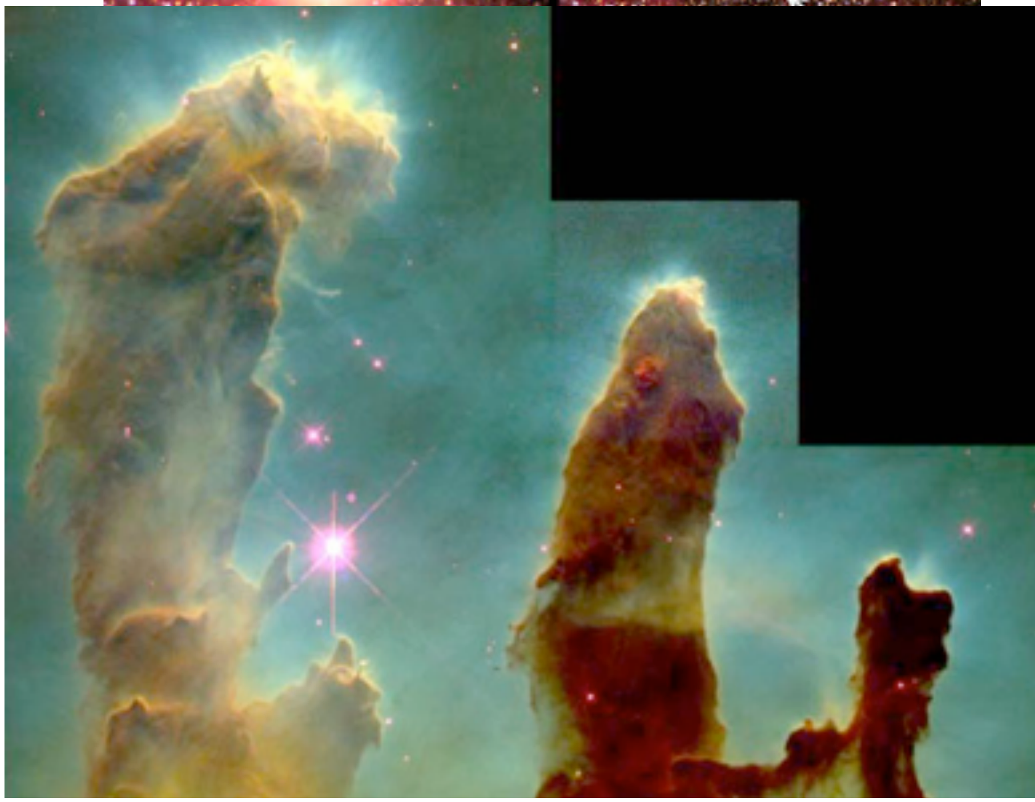
Gravity:
A Force for Death and Life in the Cosmos

Death by gravity!   Crushed star explodes!

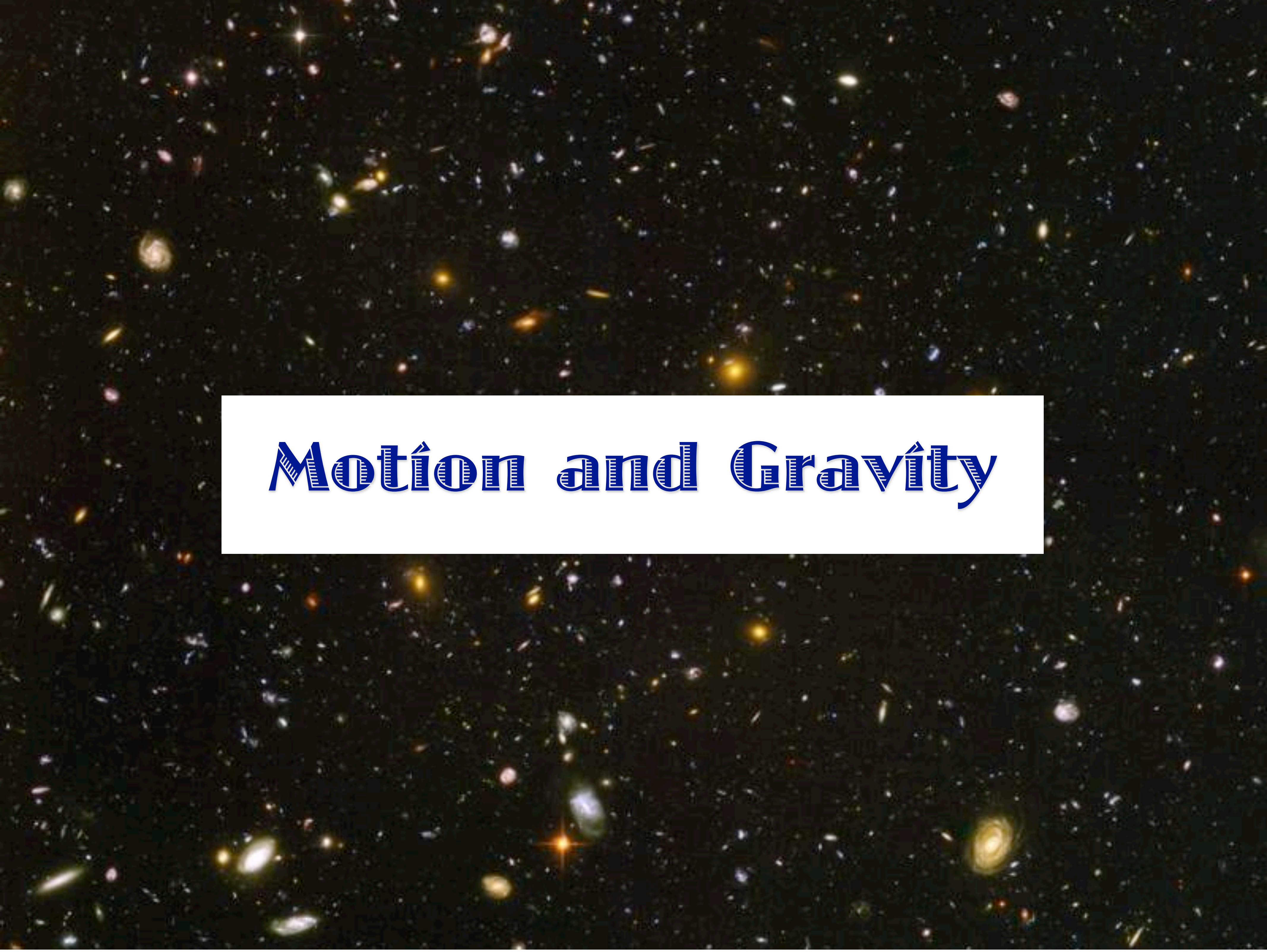
The Universe is the way it is largely because gravity is the way it is

- Gravity is ultimately responsible for most of cosmic mayhem...
- ... but also for the creation of new stars, galaxies, planets, and life

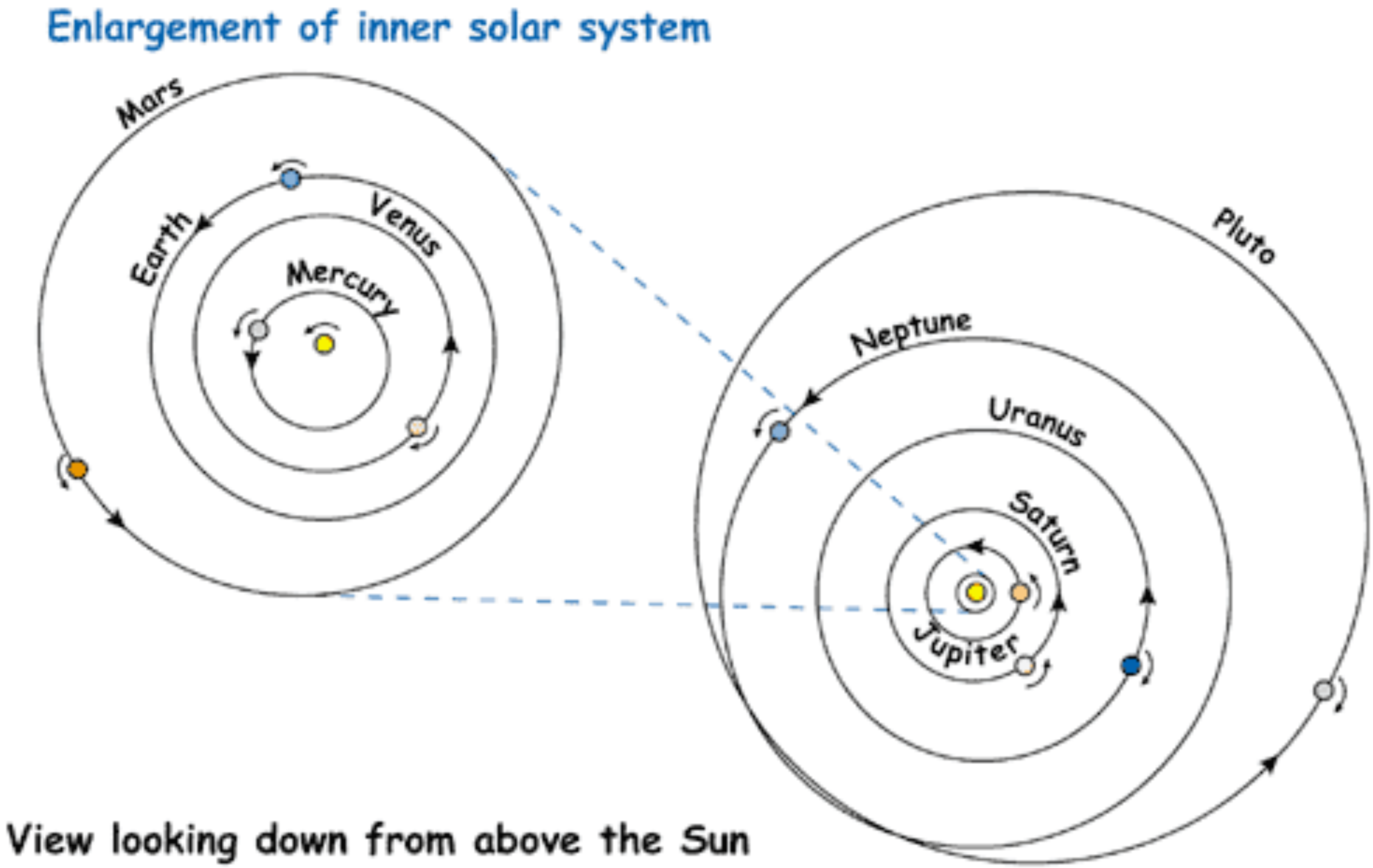
<u>Obi-Wan</u> speaks wisely: “it surrounds us and penetrates us; it binds the Galaxy together”



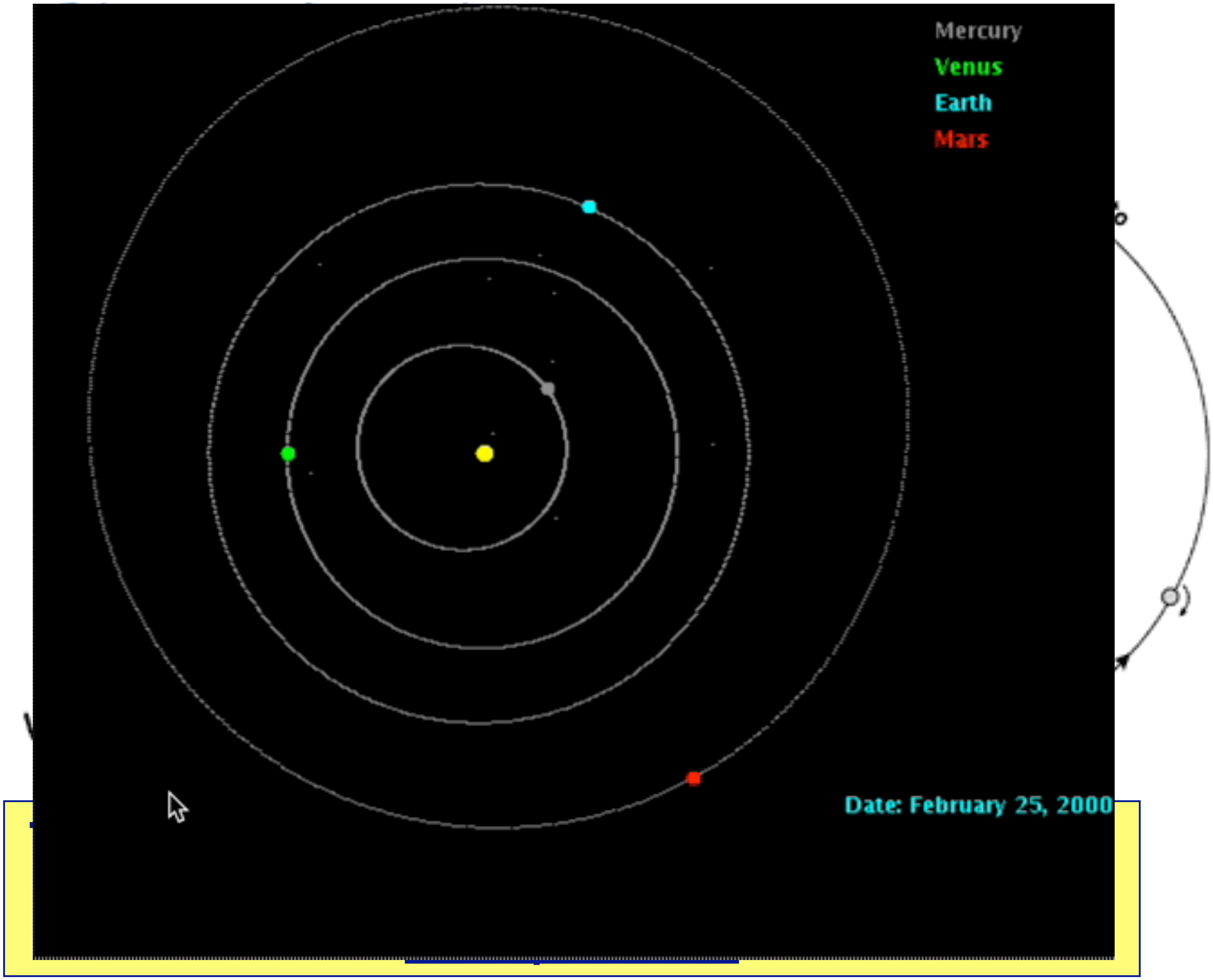
Birth by gravity! Gas clouds collapse to stars!

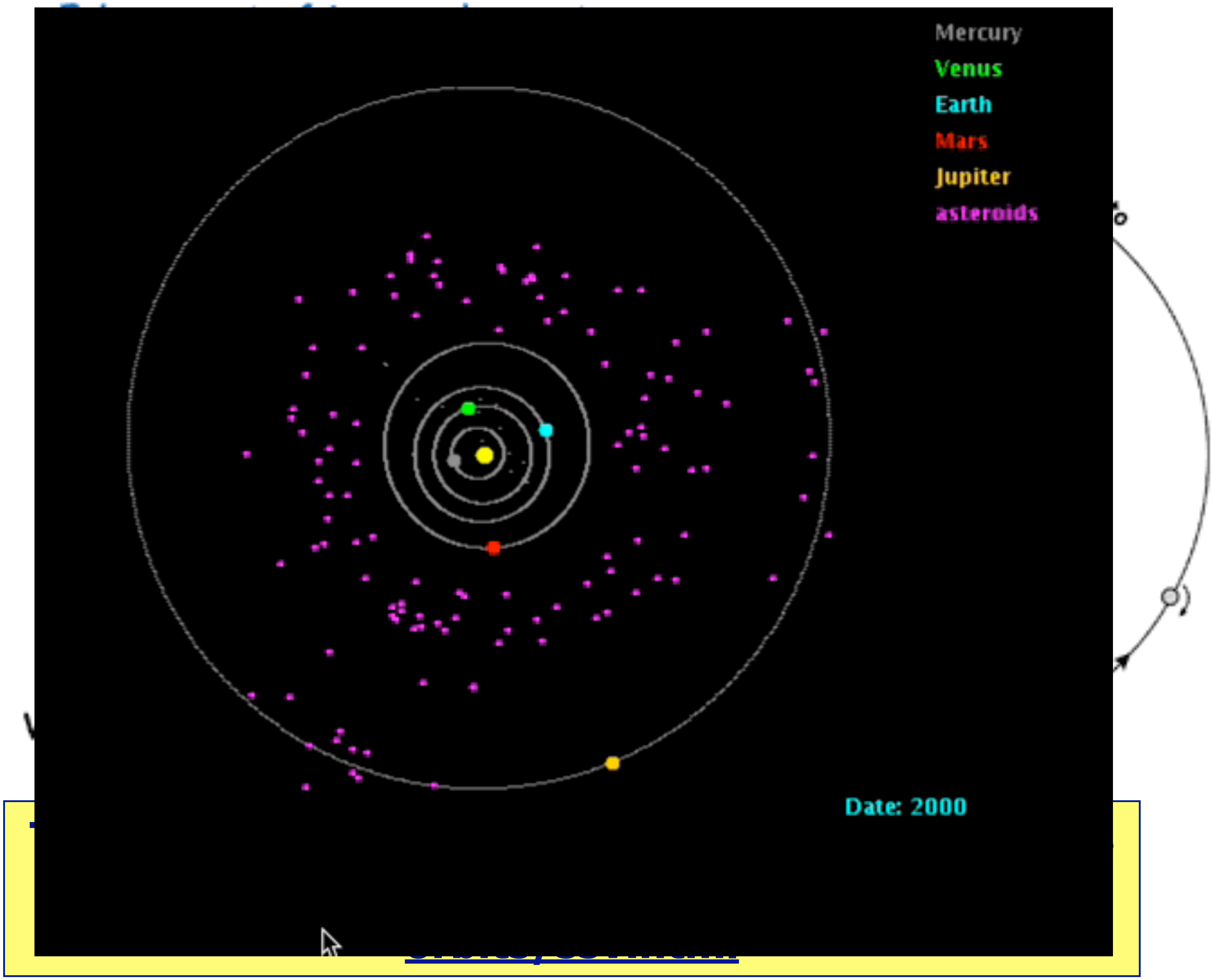


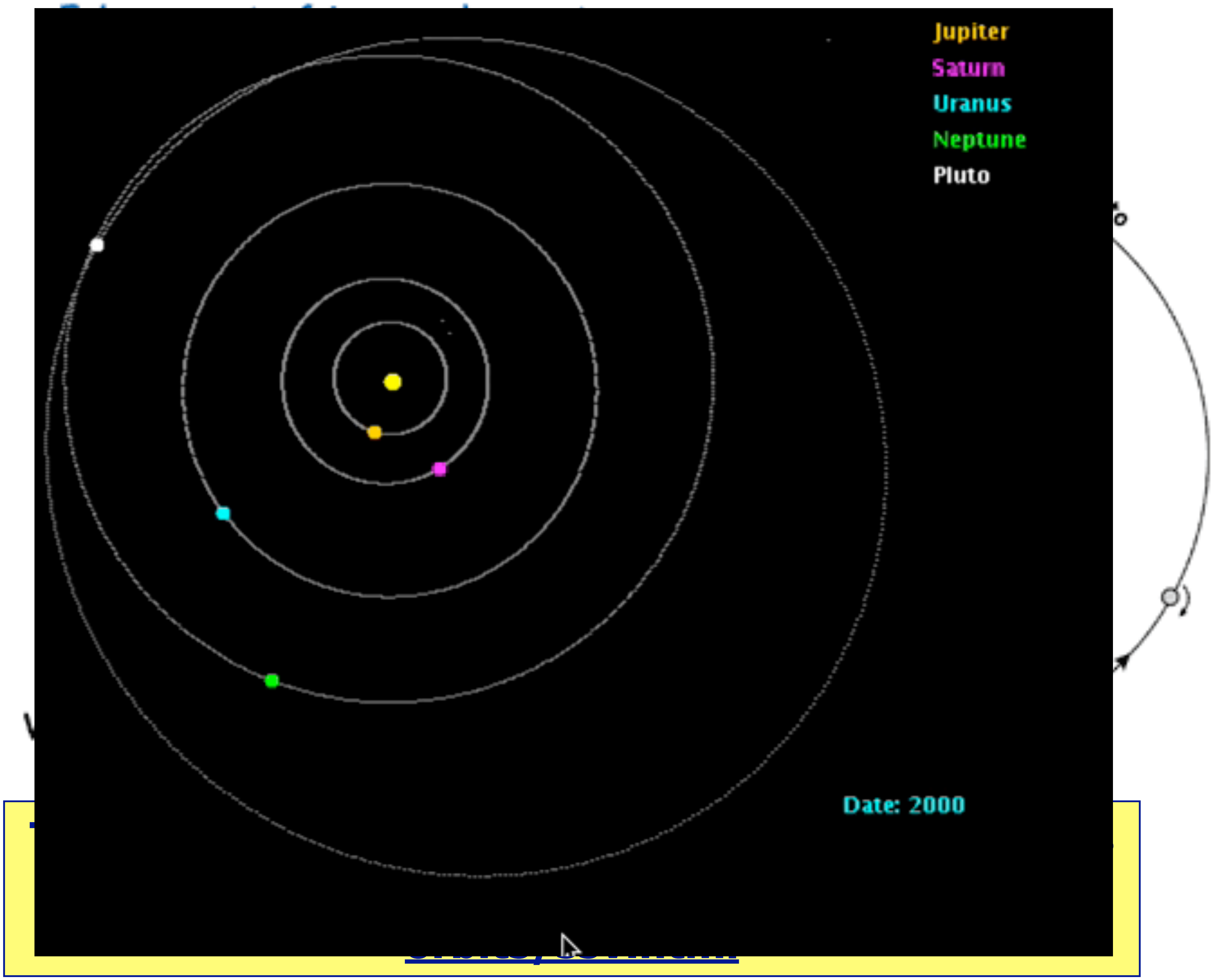
Motion and Gravity

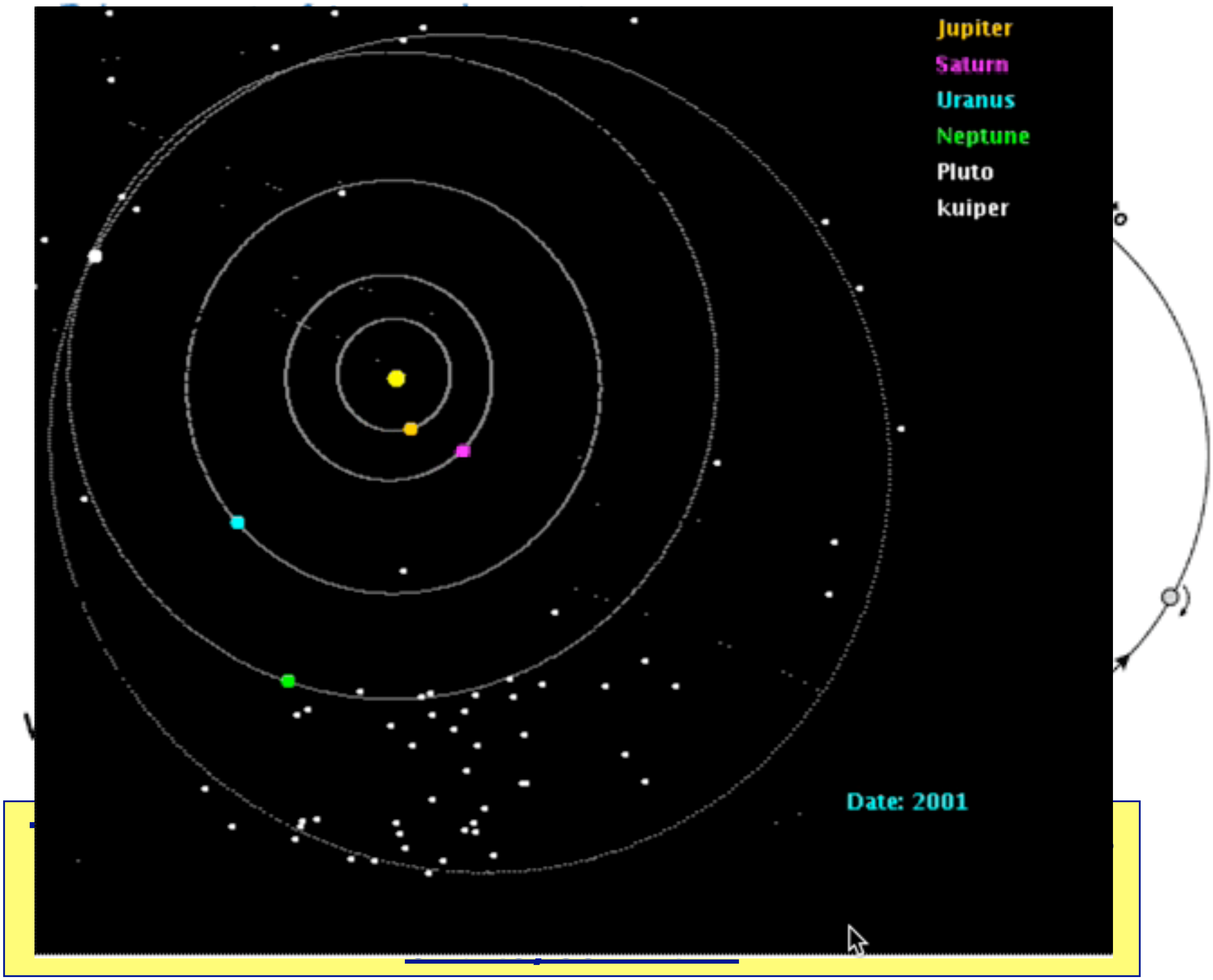


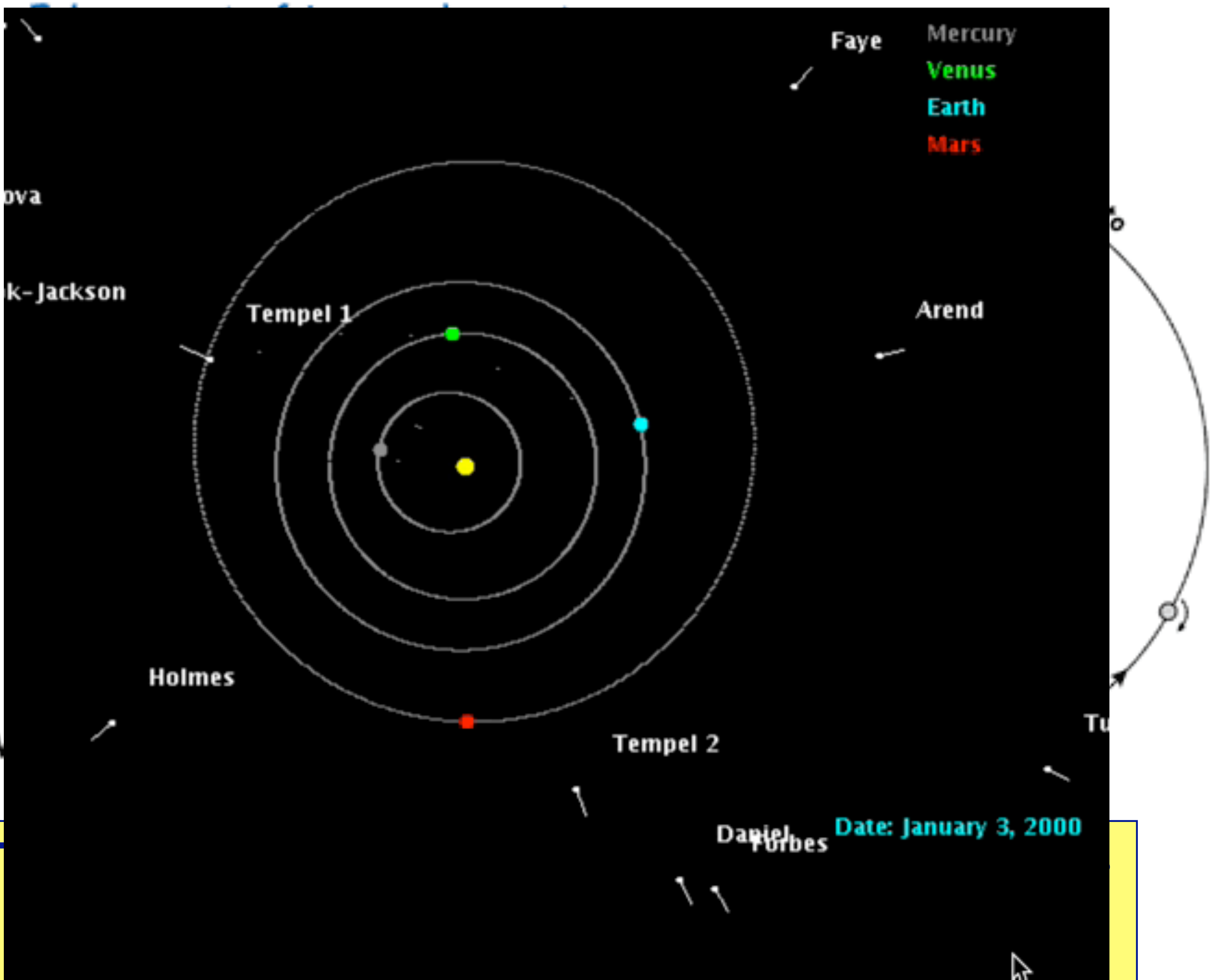
The planets orbit the Sun on nearly-circular orbits
animation: http://janus.astro.umd.edu/javadir/orbits/ssv.html


Mercury
Venus
Earth
Mars
Date: February 25, 2000


Mercury
Venus
Earth
Mars
Jupiter
asteroids
Date: 2000


Jupiter
Saturn
Uranus
Neptune
Pluto
Date: 2000


Jupiter
Saturn
Uranus
Neptune
Pluto
kuiper
Date: 2001



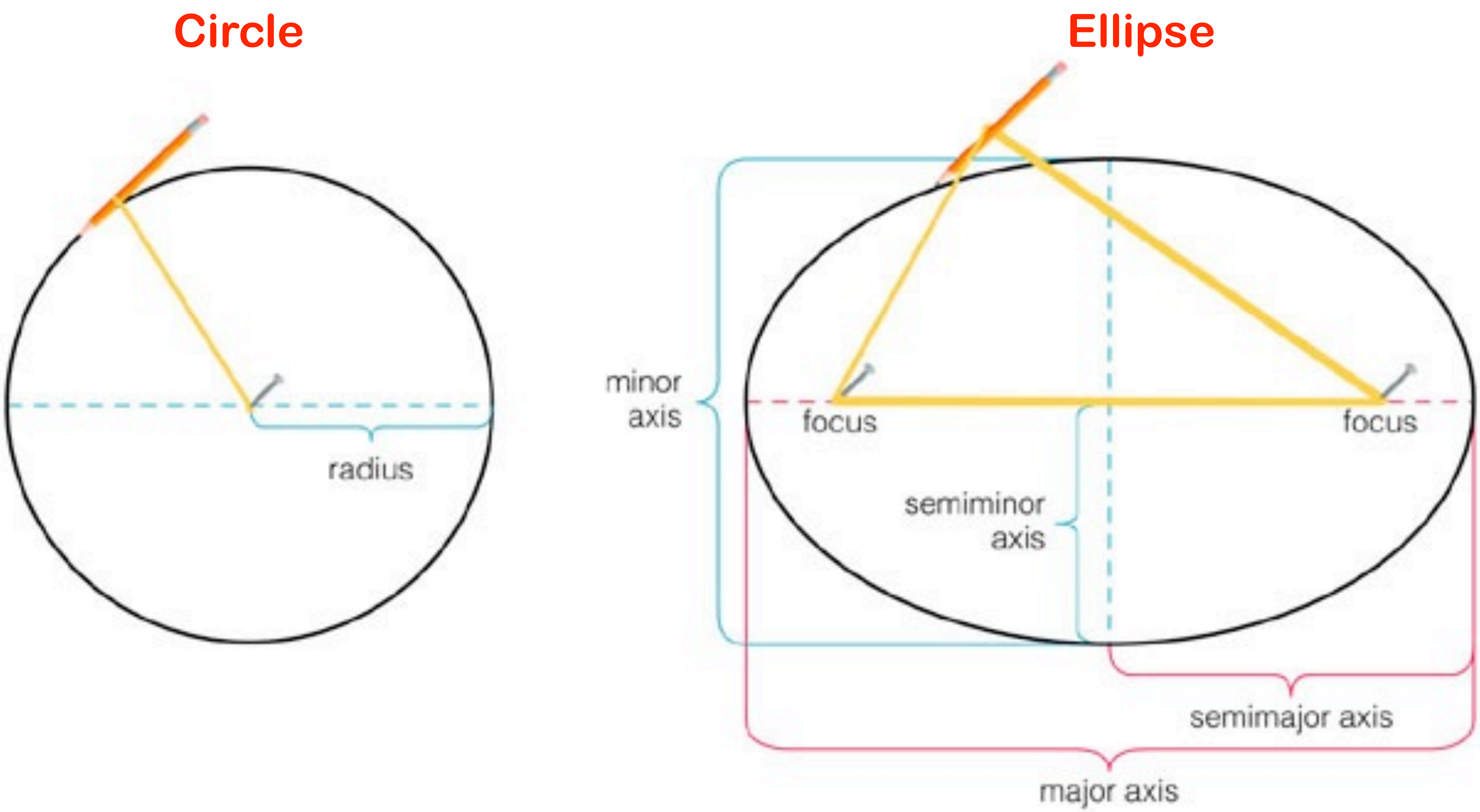
Faye
Mercury
Venus
Earth
Mars
Arend
Tempel 1
Holmes
Tempel 2
Daniel
Forbes
Date: January 3, 2000

Kepler's Laws of Planetary Motion

- 17th century astronomer
- Developed a mathematical model of orbital motions based on the ellipse
- Summarized his findings in the form of three laws of planetary motion
- Applys not only to planets but to anything orbiting Sun

Johannes Kepler (1571-1630)

What is an ellipse?



An ellipse looks like a flattened circle

It is a regular oval shape for which the sum of the distances from each point to two fixed points (called foci) is equal.

In fact a circle is just a special ellipse where both foci are at the same point!

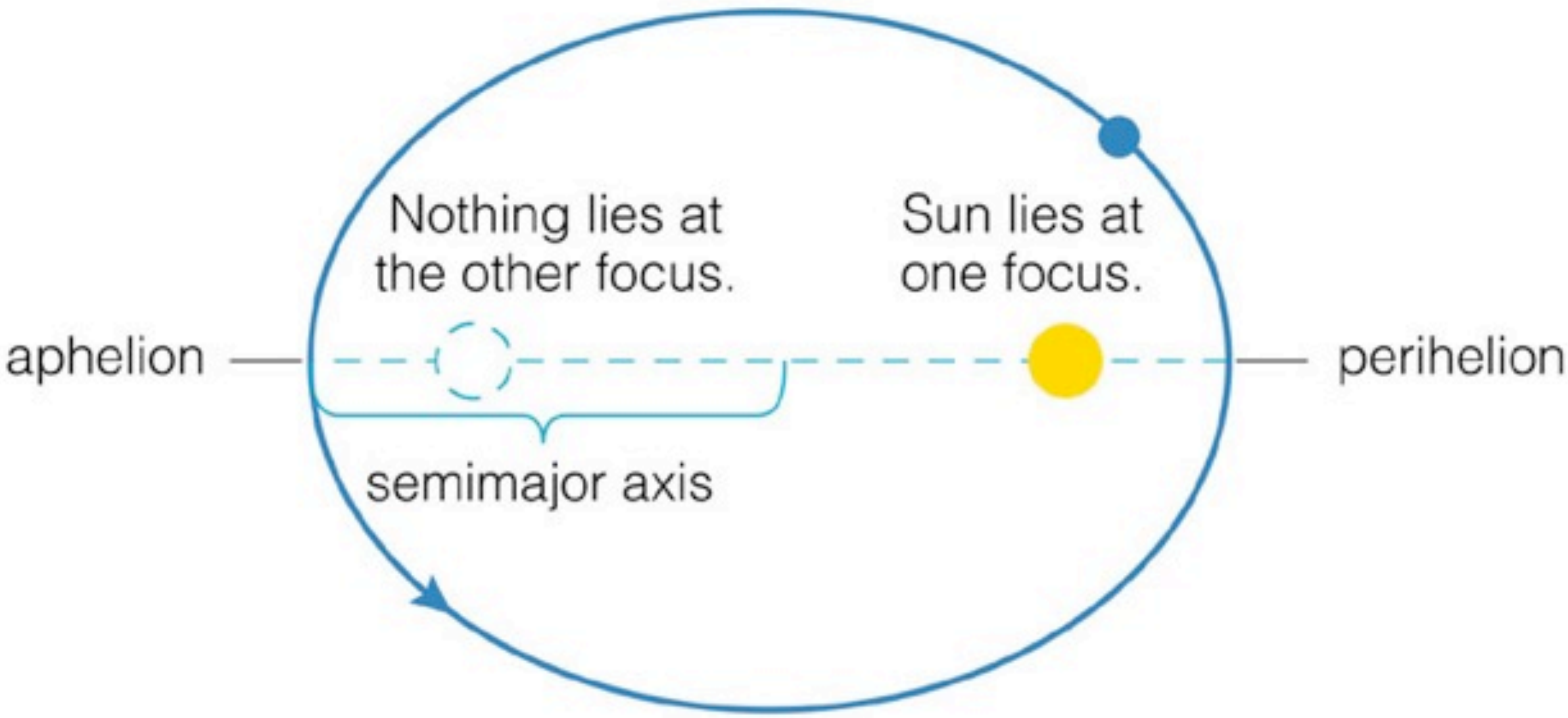
The geometry of an ellipse is described by two simple numbers.

The semi-major axis, a, is half of the longest diameter.

The eccentricity, e, is half the distance between the foci divided by the semi-major axis.

Kepler's Laws of Planetary Motion

Law #1: The orbits of the planets are ellipses with the Sun at one focus

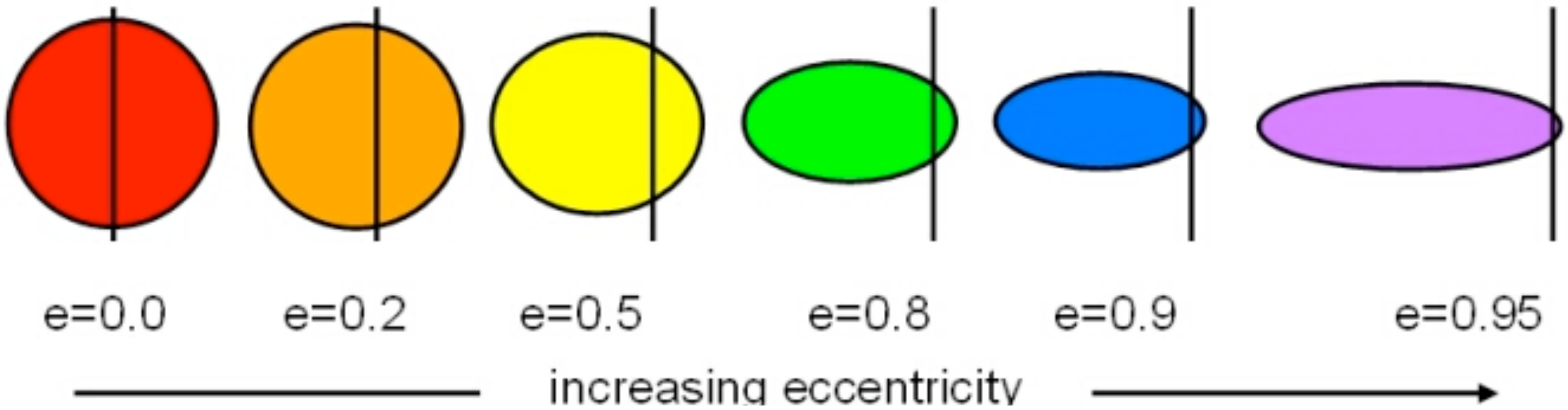


The Sun is <u>not</u> at the center of the ellipse!

Note that the Sun is not at the center of the ellipse. There is nothing at the second focus of the orbital ellipse. The planetary orbits are not very elliptical, which is why circles are fair approximations, as in Copernicus' model.

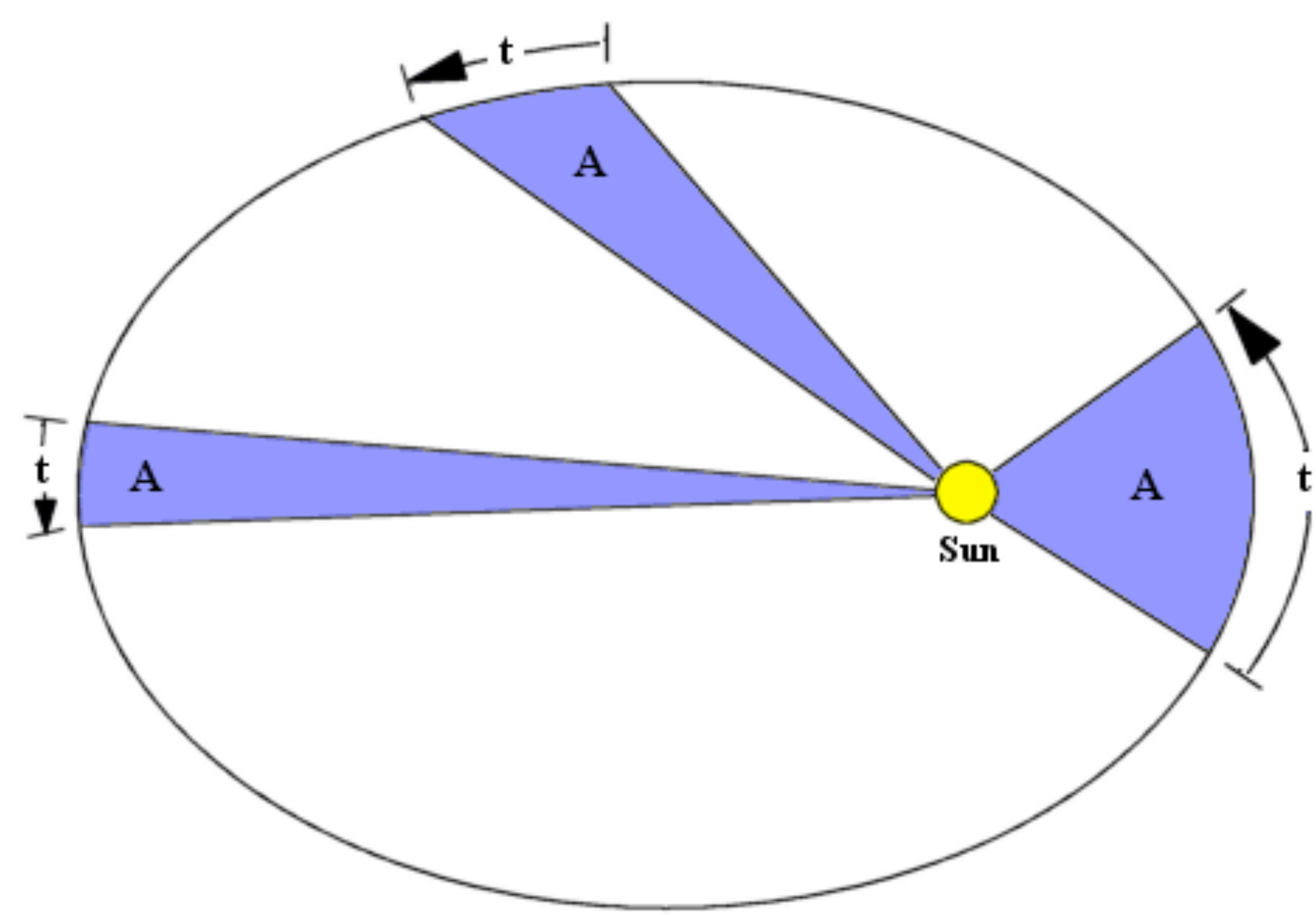
Eccentricity of an Ellipse

- Eccentricity, e, is half the distance between the foci divided by the semi-major axis
- Allowed values: e is between 0 and 1
- An e = 0 is a perfect circle while a long, thin ellipse has an e close to 1
- Most of the planets' orbits have low eccentricity - i.e. "nearly circular"



Earth's is 0.02,
Mercury's is the most eccentric planet orbit: 0.21
(Pluto was the most eccentric orbit at 0.25)
halley's comet has an orbital eccentricity of 0.97!

- **Law #2:** An line joining the Sun and planet sweeps out *equal areas in equal times*



A planet in orbit about the Sun sweeps out equal areas **A** in the same time interval **t**

Planets move faster when nearer to the Sun

- Fastest at perihelion (closest to the Sun)
- Slowest at aphelion (farthest from the Sun)

Kepler's Laws of Planetary Motion

Law #3: The square of a planet's orbital period around the Sun is directly proportional to the cube of the semi-major axis of its orbit

$$P^2 = a^3$$

Orbital period (in years)

Orbit semi-major axis (in Astronomical Units)

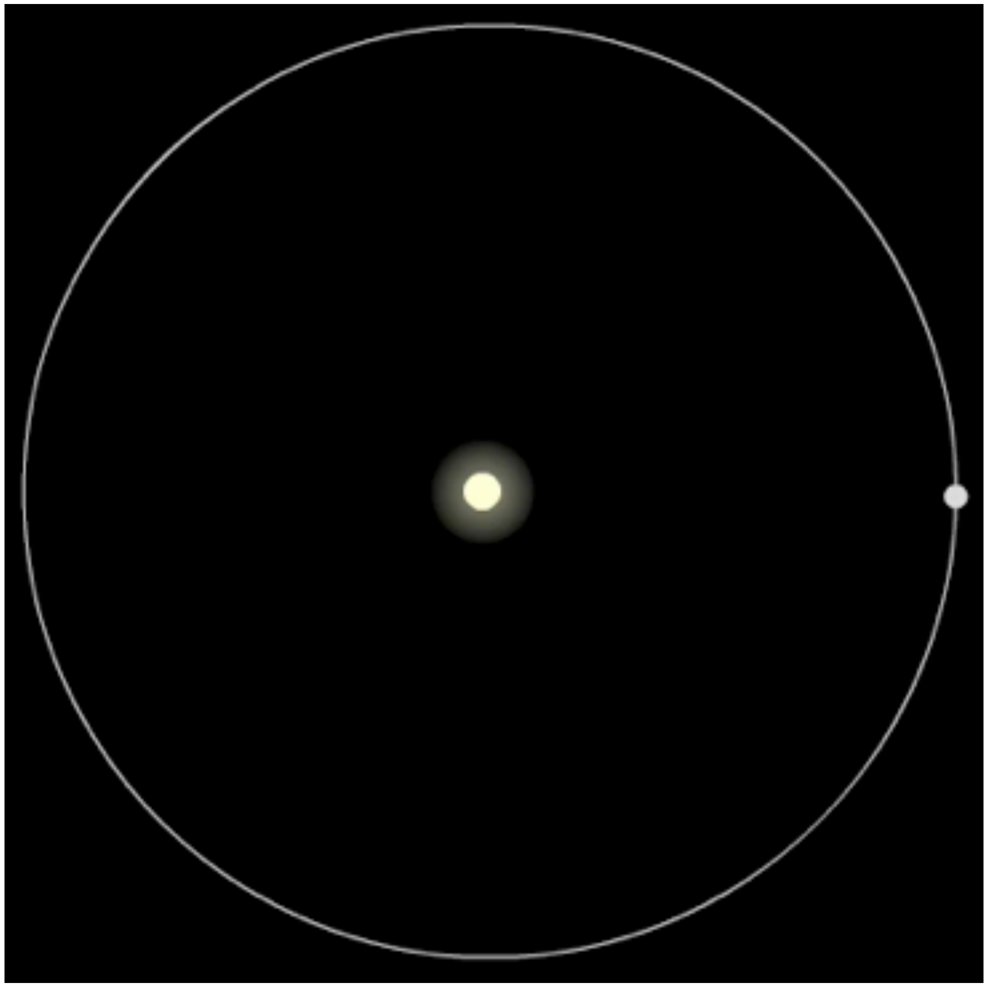
Average distance from Earth to the Sun = 1 Astronomical Unit (AU)

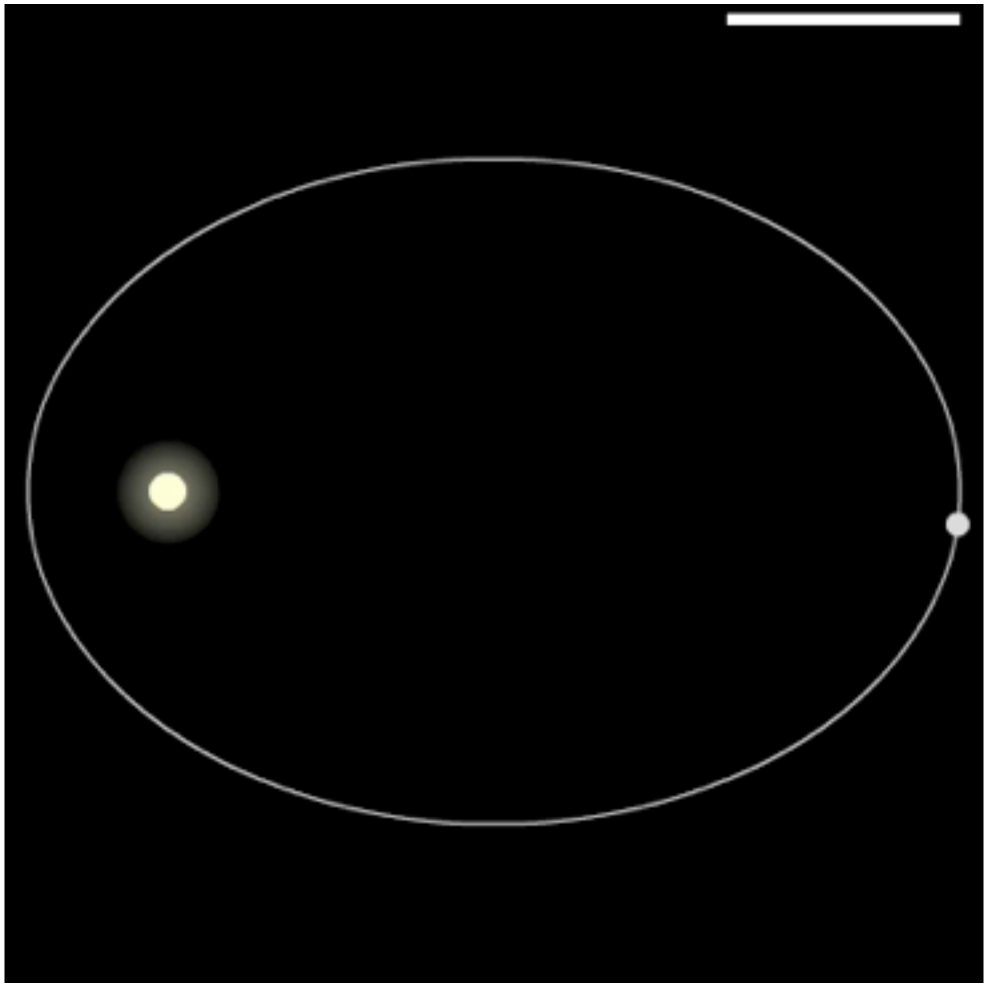
semi-major axis = average distance from the Sun

Given P to find a: $a = P^{2/3}$

Given a to find P: $P = a^{3/2}$

Kepler's 3rd Law works for orbits of any eccentricity!

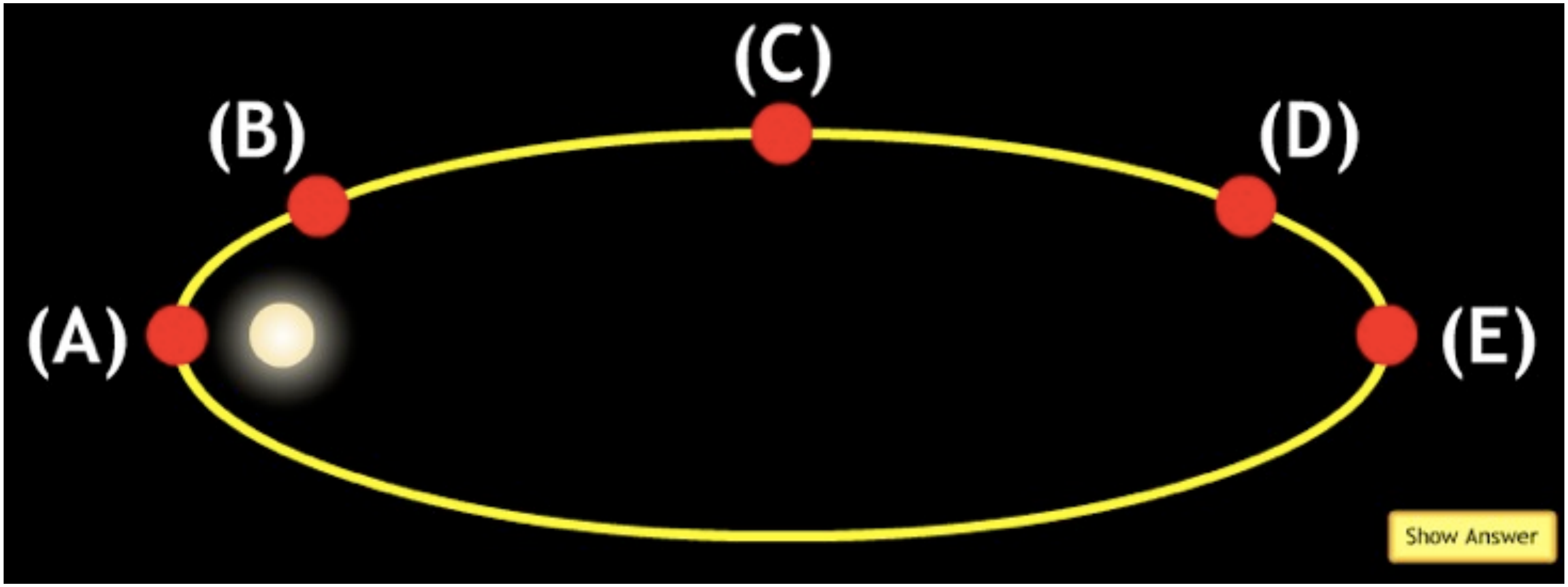




Both objects have orbits with a semi-major axis (a) of 1 AU, so both have a period (P) of 1 year

i>Clicker Question

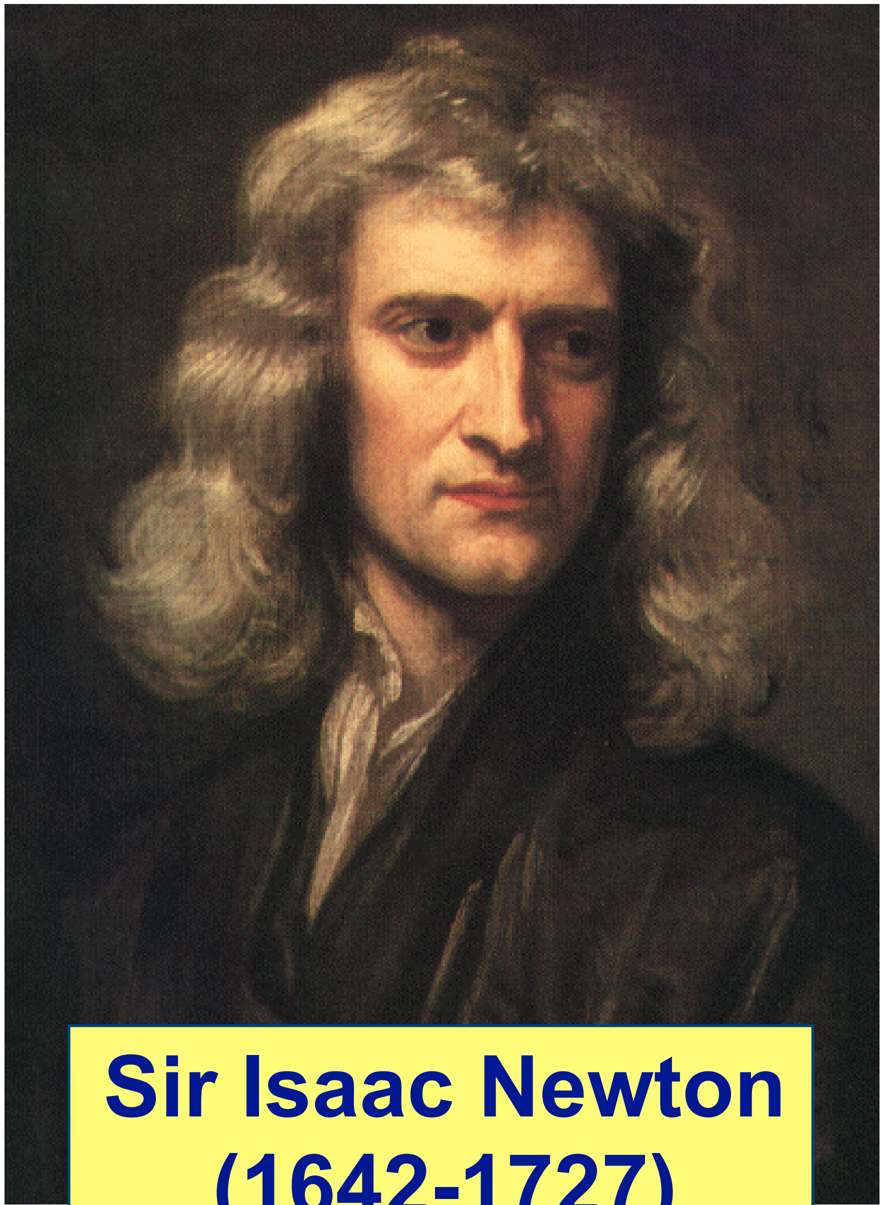
The orbit of a comet is shown below. At which point in the orbit would the comet's speed be lowest?



Answer E

Why do the planets move they way they do?

- Newton's answer: GRAVITY
- He developed some basic rules governing the motion of all objects
- Used these laws and Kepler's Laws to derive his unifying Law of Gravity



Sir Isaac Newton (1642-1727)

Kepler's Laws describe how the planets move, but not the reasons why

Newton's life represented the flowering of the seeds planted by the previous four astronomers in this story—Copernicus, Tycho, Kepler, and Galileo.

From his study of the work of Galileo, Kepler, and others, Newton extracted three laws that relate the motion of a body to the forces acting on it.

Describing Movement

Need precise language not just for planets but for all moving objects

Speed: rate of motion

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

Velocity: speed and direction of travel

Q: Can two objects have same speed, different velocity?

Q: Does a car's "speedometer" really measure speed or velocity?

Acceleration

Acceleration:

change in speed or direction of motion

but velocity is speed and direction, so acceleration is change in velocity

Intuitively: acceleration is rate of speeding up or slowing down

sometimes useful to distinguish

- acceleration=speed up
- deceleration=slow down

But, acceleration also means changing direction without speeding up or down.

Motion: Special Cases

Galileo Galilei

Special Motion I: "Free Body"

moving with no external influences

(including friction, gravity)

Free body moves in

- straight line,
- with constant speed
- = constant velocity

Galileo: this is "natural motion" of objects

keep speed and direction unless something happens to change this

Motion: Special Cases

Tower of Pisa

Special Motion II: "Free Fall"

motion due to gravity only

Demo: Tower of Pisa Experiment

Q: in free fall, is velocity constant?

even if fall in straight line, speed changes

- gravity causes acceleration
- same acceleration for all objects
  independent of size, mass
- http://www.youtube.com/watch?v=_Kv-U5tjNCY

Motion: Special Cases

Tested on the Moon too!

Tower of Pisa

Explaining Motion: Isaac Newton

Newton:

- Why Kepler's laws for planets?
  - Are planets special?

Can we understand general rules for motion?

New concepts

- mass = "amount of stuff"
  - measure in kilograms (kg): 1kg of anything has same mass
- force = push or pull on an object
  - can have more than one force acting, in different directions
- net force = total of all forces acting
  - if forces unbalanced, net force is present

Explaining Motion: Newton's Laws

Forces & motion linked

Newton I. "Inertia"

What if no forces act?

- An object at rest stays at rest if no forces act on it
- A moving object goes in straight line with constant speed if no forces act on it
  - That is, constant velocity

Newton I describes free bodies

Explaining Motion: Newton's Laws

Newton II. "F=ma"

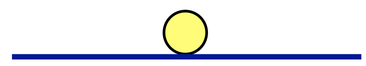
What if forces act?

$$\text{Force} = \text{mass} \times \text{acceleration}$$

- A net force on an object causes it to accelerate
- More force, more acceleration
- More massive objects harder to accelerate

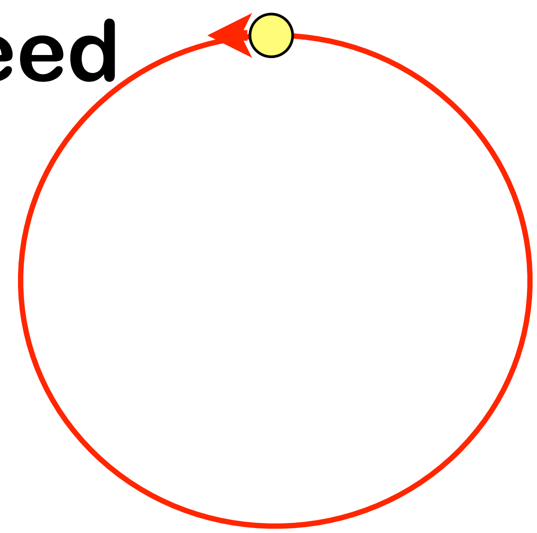
Newton II: F=ma

Example: ball on table, at rest



- *Q: how many forces? net force?*
- at rest so a = 0 and thus F = 0: no net force
- but one force for sure: gravity downwards
- so must be another force upwards: table pushes back
  - (test: yank table away, ball falls)

Example: move in circle, constant speed



- changing direction: changing velocity
- must be acceleration
- must be force

Explaining Motion: Newton's Laws

Newton III. "Action/Reaction"

a rule for how forces behave between objects

if 2 bodies interact

- the force exerted by object 2 on object 1 is equal to but opposite in direction to
- the force exerted by object 1 on object 2

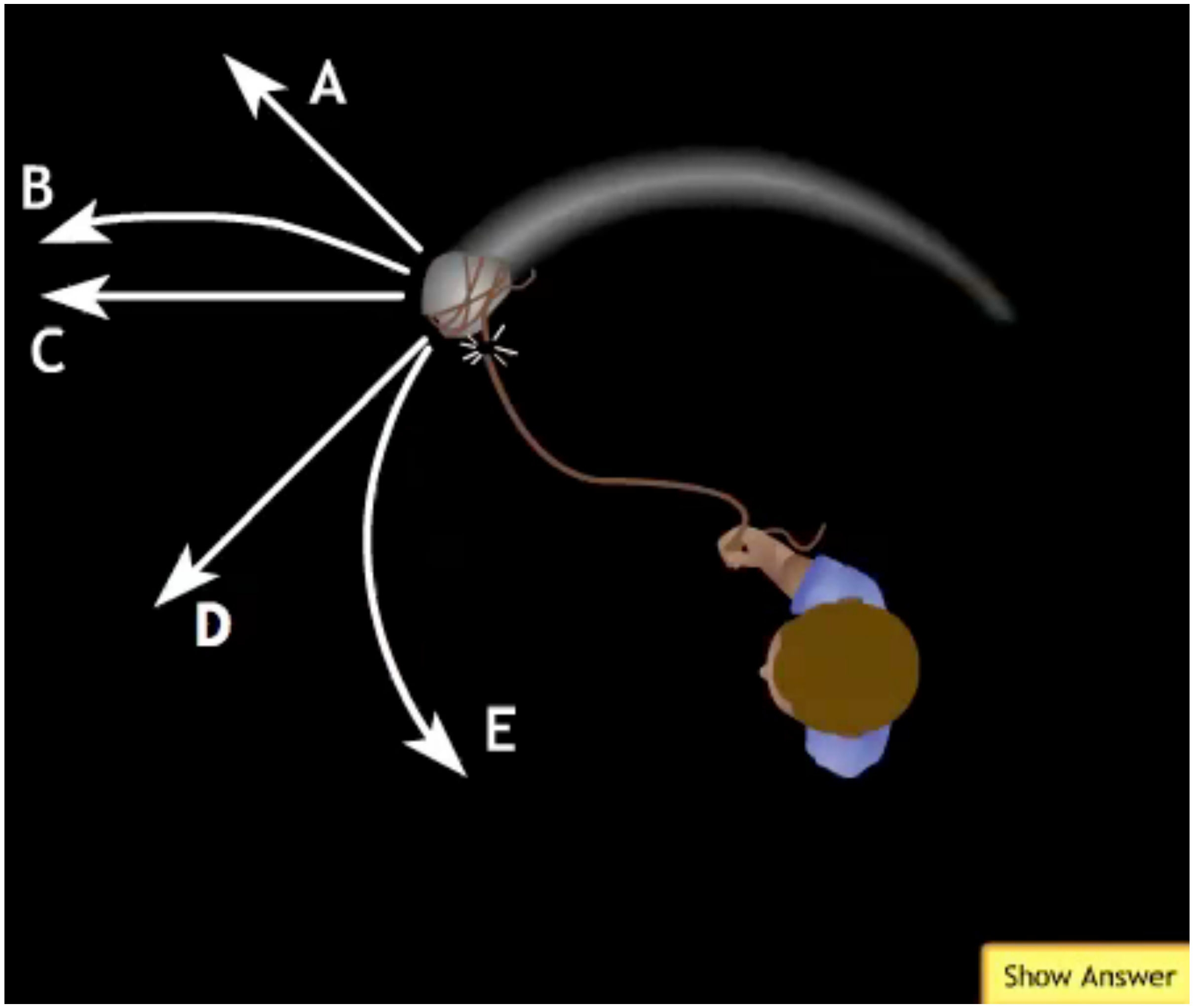
Example: you standing still

- your force on floor (weight) downward is
- same as floor push upwards on you

Example: Jump shot

i>Clicker Question

A boy is spinning a rock tied to a rope horizontally above his head. In which direction will the rock go if the string breaks?

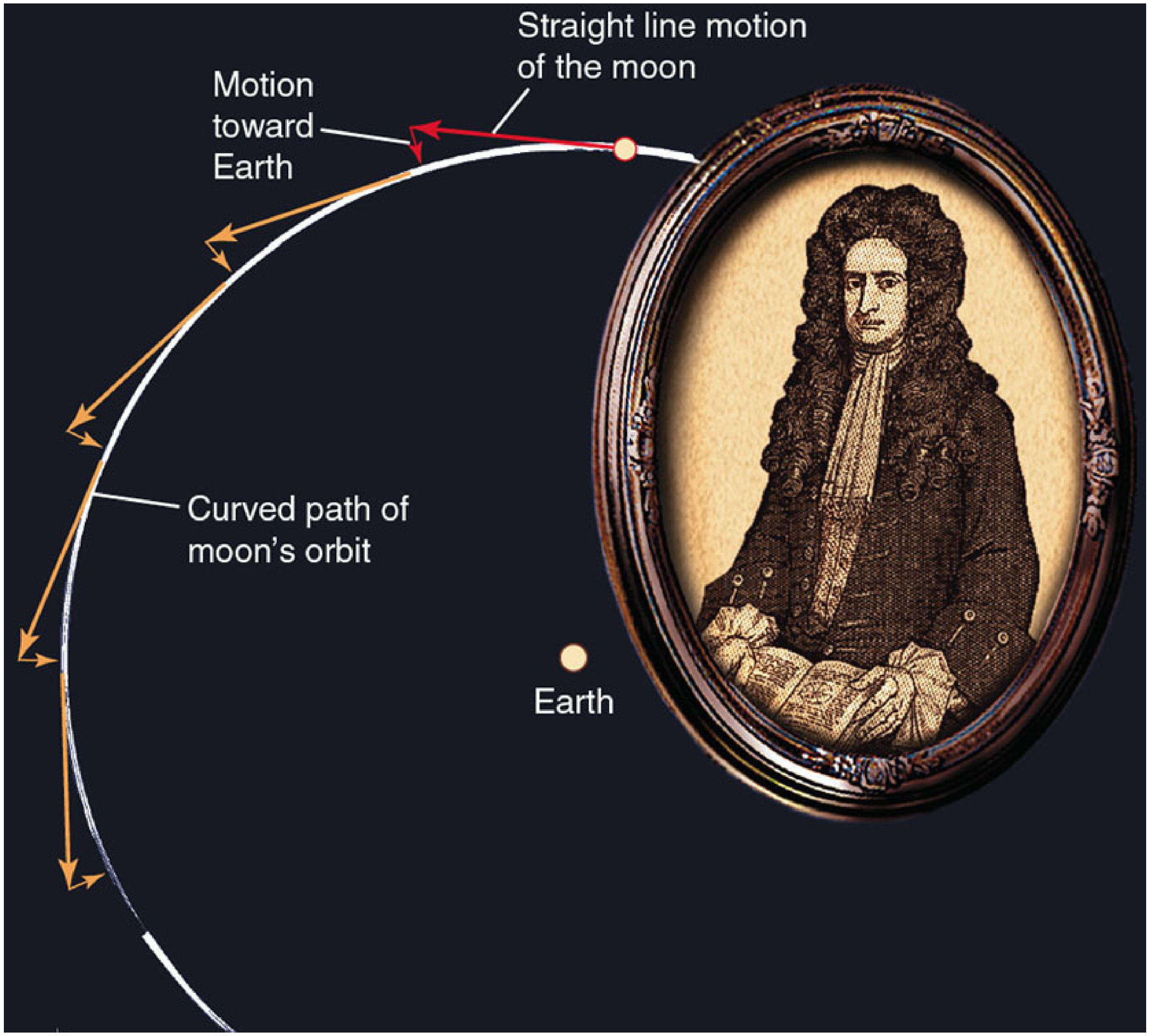


Curved path: changing direction = changing velocity = acceleration
But *F=ma*: so acceleration requires force!

Answer D
Newton's first law – with no force acting on the rock it flies in a straight line.
Was the rock accelerating when the boy was spinning it over his head? Yes
Was there a force acting on it? Yes – the string was pulling on the rock
In what direction? Towards the center.

A force must pull the Moon toward Earth's center

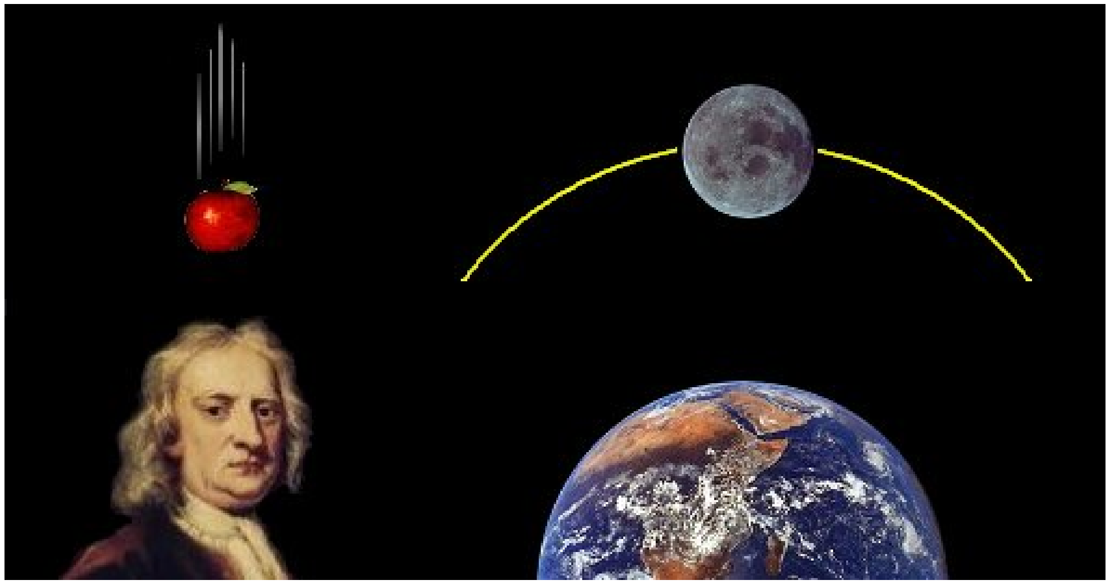
If there were no force acting on the Moon, it should follow a straight line and leave Earth



But, for every 1,020 meters it moves eastward, it falls 1.6mm toward Earth
So, there must be a force acting on it

Newton's Great Insight

- The same force makes things fall down on Earth and keeps the planets in their orbits
- Gravity!
- Newtonian gravitation is sometimes called universal gravitation



Gravity makes apples fall from trees and keeps the Moon orbiting the Earth

Why? Newton's third law points out that forces occur in pairs.
If one body attracts another, the second body must also attract the first with the same force. Thus, gravitation must be mutual.
Furthermore, gravity must be universal. All objects that contain mass must attract all other masses in the universe.

Universal Gravitation

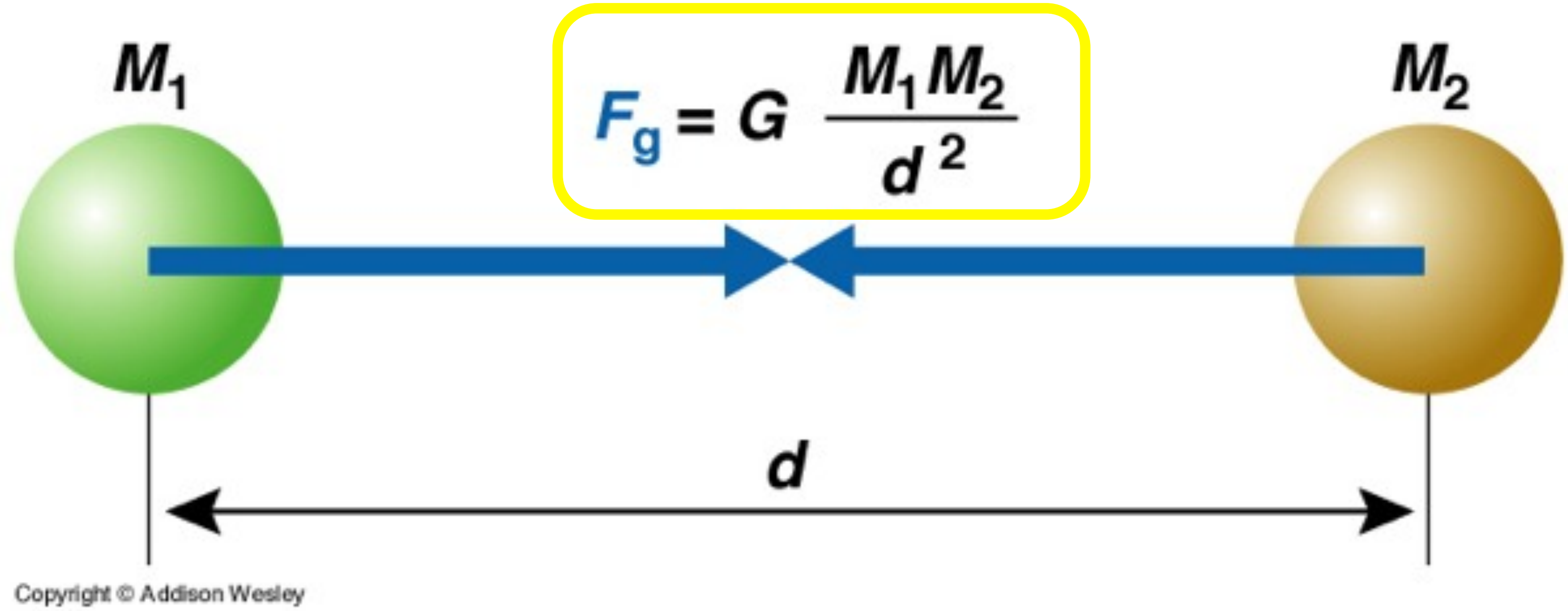
Newton's law of gravity combines these ideas:

- Gravity is attractive: gravity force between two objects pulls each towards the other
- The force of gravity acts beyond the Earth
  - "reaches out" into space
- Gravity strength decreases with distance
- The source of gravity is mass
  - All objects with mass are sources of gravity
  - everything attracts everything else in the universe!

Universal Gravitation Law

Summarize gravity properties in compact way

- For two masses separated by distance d
- Gravity force proportional to the product of their masses
- Gravity force inversely proportional to the square of the distance between their centers
  - “inverse square law”
  - In equation, G is just a fixed number (grav. constant)



iClicker Poll: Inverse Square Law

The force of gravity on you is your weight.

If you go into space and double your distance from the center of the earth, your weight will be

A. 2 times stronger
B. 4 times stronger
C. 2 times weaker
D. 4 times weaker
E. your weight cannot change just by relocating

Guaranteed weight loss: go to space!

Gravity and Planet Motion

$F = ma$: for planets, force is gravity only: free fall

So: find acceleration when

$$F = F_{\mathrm{grav}} = G\frac{m_{\mathrm{planet}} m_{\mathrm{sun}}}{d^2}$$

acceleration gives change in velocity

- ...which tells where move to next
- ...where there is a new acceleration
- and so forth: $F_{\mathrm{gravity}} = ma$ predicts orbit

What is prediction?

- Orbits are ellipses, with Sun at one focus
- Equal areas in equal times

$$P^2_{\mathrm{in\ years}} = a^3_{\mathrm{in AU}}$$

So: Newton's laws + gravity gives Kepler's laws

theory agrees with observation! Woo hoo!

iClicker Poll: Uranus Discrepancy

It's 1830. You are a famous Astronomer.

Measured Uranus orbit doesn't match predictions of Newtonian Gravity theory.

Vote your conscience!

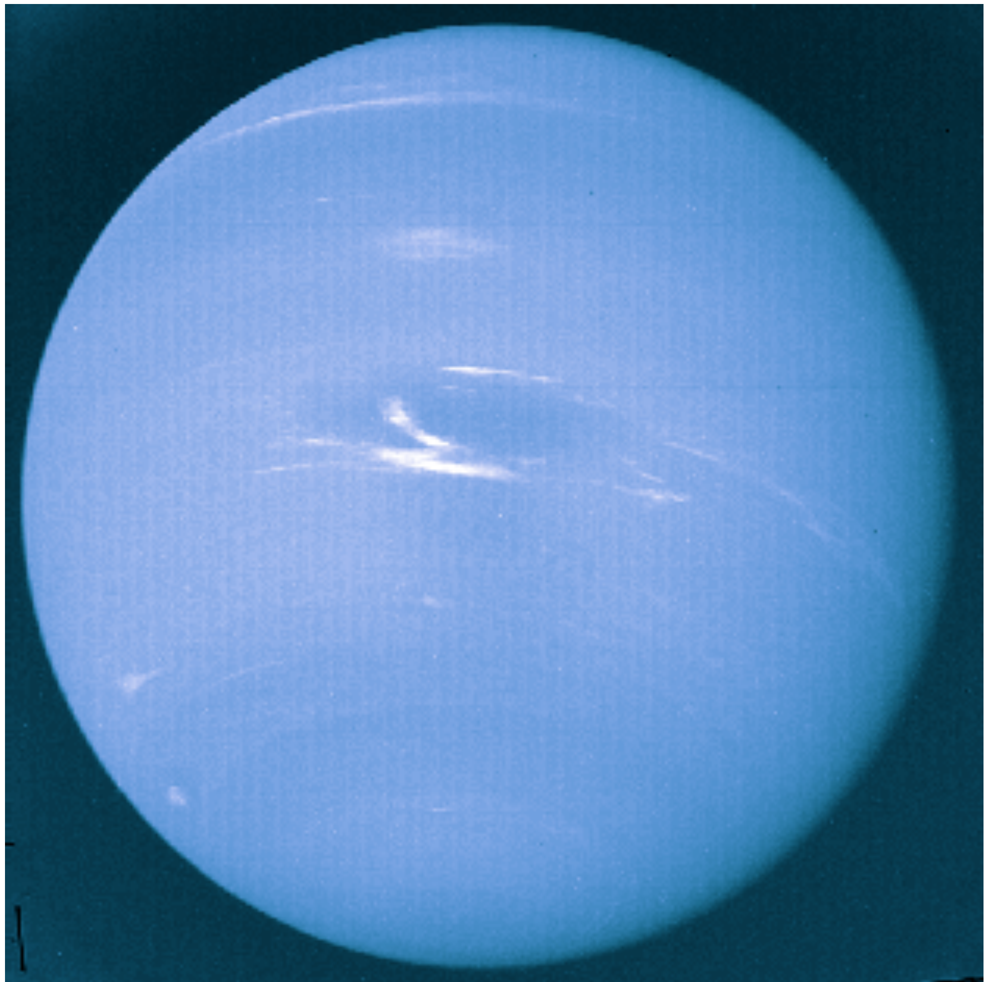
Which seems more likely to you?

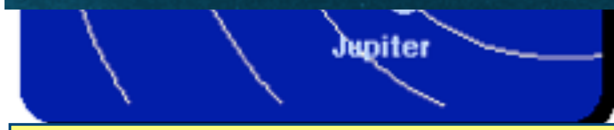
A. **Newton's gravity theory correct, but not all gravity sources included**

B. **Newton's gravity theory incorrect (or at least incomplete)**

Q: What experiment/observation would tell which is right?

Mystery of the Crazy Orbit Solved by Observations





- Astronomers noted discrepancies between Uranus' orbit and calculations
- Predicted the position of an unknown planet based on its gravity perturbations
- the race was on to scan this region of sky, and....
- Neptune was found at almost exactly the predicted location!
- Existence of Neptune predicted by Newton's laws!

Questions?

Uranus' orbit is *perturbed* by the other planets

This precise prediction of the new planet and its location was striking confirmation of the power of Newton's theory of gravitation.