AST 301
Introduction to Astronomy

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Topics for this week

How did Kepler improve on Copernicus' model?

State (and define the term in) Kepler's laws.

Speed, velocity, acceleration, mass, force, weight

Newton's three laws of motion

Newton's law of gravity

Orbital motion explained with Newton's laws

Falling objects explained with Newton's laws

The test on Friday will cover chapters 1-4, including Newton's laws

Kepler's laws (or rules)

1. The planets move on elliptical paths with the Sun at one focus of the ellipse for each planet.

2. The speed of a planet changes during its orbit, moving fastest when it is closest to the Sun and slowest when it is farthest from the Sun.

   A line from the Sun to the planet sweeps out equal areas in equal times.

3. Different planets move at different speeds, with a planet in a smaller orbit moving faster than one in a larger orbit.

   The time for a planet to orbit the Sun depends on the size of it orbit according to the rule:

   $P^2 = a^3$, where P is in years and a is in AU

Kepler's 2nd law and proportions

One way of stating Kepler's 2nd law is to say:

The speed of a planet at different places in its orbit is inversely proportional to its distance from the Sun.

This means that if it is twice as far from the Sun in one location than another, it moves ½ as fast at that location.

$v \alpha 1/r$

We will be able to state Kepler's 3rd law in a similar way:

The average speed of a planet (when we compare it to a different planet) is inversely proportional to the square root of its average distance from the Sun (a).

$v \alpha 1/r^{1/2}$

Galileo’s contributions to science

In addition to his support of the Copernican model of the Universe, Galileo argued that science should be based on observations and experiments, not on pure thought.

In his book, “Dialogues on Two New Sciences” he began the modern study of motion and materials.

Galileo’s most famous experiment was dropping two balls off of the leaning tower of Pisa.

Most people thought the heavier ball would fall faster.

What actually happened?

About 100 years later, Newton continued Galileo’s study of motion (and other sciences).

Newton’s theory of motion

Common experience tells us that you have to push on an object to make it move and the harder you push the faster it goes.

If you stop pushing on an object it will stop moving.

Newton realized that this is a result of a complicated situation involving friction.

In a simple situation (like an object in space or a very smooth ball rolling) the rules are different.

And the rules for simple situations can be combined to explain motion in complicated situations.

Newton also realized that his laws of motion when applied to the planets could explain Kepler’s laws.

Definitions

speed: distance traveled / time spent traveling

acceleration: change of speed / time spent changing

(can also be a change in direction of motion)

force: how hard one object pushes or pulls on another

mass: is a measure of the amount of matter in an object and how much it resists being pushed around

volume: the amount of space an object takes up

for a box: height x width x depth

Newton's laws of Motion

1. If there are no forces acting on an object, if moving it will continue to move with constant speed and in the same direction. If not moving, it will remain stationary.

2. If a force is acting on an object, the object's acceleration (the rate of change in its speed or direction of motion) is proportional to the force acting on it and is inversely proportional to its mass.

   $a \alpha F / m$

3. If an object exerts a force on a second object, the second object necessarily exerts the same force on the first, but in the opposite direction.

Quiz

If I step on my brakes and slow down from 60 mph to 30 mph, am I accelerating?

A. yes

B. no

By scientists’ definition any change in speed is called acceleration, whether an increase or a decrease.

If I take my foot off of the gas and coast around a corner at constant speed, am I accelerating?

A. yes

B. no

Quiz

If I push on my car for 5 seconds I can make it move at 2 mph. If I pushed for an additional 5 seconds with the same force, how fast would it then be going? Ignore all other forces acting on the car.

A. 2 mph
B. 4 mph
C. 7 mph
D. 10 mph

Quiz

If I push on my car for 5 seconds I can make it move at 2 mph. If two identical cars were lined up bumper-to-bumper, how fast could I make them move by pushing (with the same force) for 5 seconds?

A. 0 mph

B. 1 mph

C. 2 mph

D. 4 mph

Again, ignore all other forces acting on the cars.

Newton's law of gravity

Gravity is a attraction between any two objects.

The force of gravity is proportional to the product of the masses of the two objects and is inversely proportional to the distance between their centers.

$$F \alpha m_1 m_2 / d^2$$

or

$$F = G m_1 m_2 / d^2$$

Quiz

When the Apollo astronauts were on the way to the Moon, 10 Earth radii away from the Earth (1/6 of the way to the Moon), what was the force of gravity on a 150 pound astronaut?

A. 0
B. 1.5 lb
C. 15 lb
D. 150 lb

Newton's explanation of Galileo's experiment

If the two balls that Galileo dropped from the leaning tower had different masses, the force of gravity on them should have been different. Why did they fall at the same rate?

What if one ball had a mass of 1 kilogram and the other had a mass of 2 kg? The force of gravity on the 2 kg ball was twice the force on the 1 kg ball and Newton's 2nd law says that acceleration is proportional to the force on an object.

But Newton's 2nd law also says that acceleration is inversely proportional to the mass of the object.

Doubling the force and doubling the mass have opposite effects, resulting in the same acceleration for the two balls.

Galileo (and Einstein) just argued that all objects accelerate the same under the influence of gravity. Newton explained that by saying that the force of gravity is proportional to mass, and acceleration is proportional to force / mass.

If the force of the Earth's gravity on a 1 kg ball is 10 Newtons, what is the force of the ball's gravity on the Earth?

A. much less than 1 Nt.
B. 1 Nt
C. 10 Nt.
D. much more than 10 Nt.

Newton's version of Kepler's 3rd law

Newton's laws can be used to derive Kepler's 3rd law.

A force is needed to cause a planet to move on a curved path. That force is the force of gravity of the Sun.

By equating the force of the Sun's gravity to the force needed to cause a planet to follow a curved path, we can calculate the speed of the planet.

The result is: $v = (G\, M_{Sun} / a)^{1/2}$,

where v is the average speed of the planet, M_{Sun} is the mass of the Sun, and a is the average distance of the planet from the Sun.

Knowing the speed of the planet, we can calculate the time it takes to orbit the Sun.

The result is: $P^2 \alpha\, a^3 / M_{Sun}$

The Math

$F_{\text{on Earth}} = G\, M_{\text{Earth}}\, M_{\text{Sun}} / r^2$

$a_{\text{of Earth}} = F_{\text{on Earth}} / M_{\text{Earth}} = G\, M_{\text{Sun}} / r^2$

$a_{\text{in orbit}} = v^2 / r$

for $a_{\text{of Earth}} = a_{\text{in orbit}}$ we need:

$G\, M_{\text{Sun}} / r^2 = v^2 / r$, or

$G\, M_{\text{Sun}} = v^2\, r$, or $v^2 = G\, M_{\text{Sun}} / r$

but we also know that v = distance/time = $2\pi r / P$, so

$G\, M_{\text{Sun}} = (2\pi r / P)^2\, r = 4\, \pi^2\, r^3 / P^2$, or

$P^2 = (4\, \pi^2 / G\, M_{\text{Sun}})\, r^3$, or $P^2 \propto r^3$

(and for a circle, $r = a$, the semimajor axis)