November 24, 2010 Physics 121 Prof. E. F. Redish

- **Theme Music:** **John Mayer**
  Gravity*
- **Cartoon:** **Bill Watterson**
  Calvin & Hobbes

*Thanks to Scott Morski for suggesting this song!

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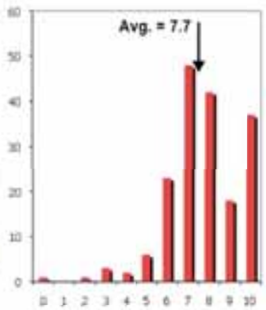
Quiz 9

	9.1		9.2	9.3
a	2%	a>b>c>d	1%	12%
b	1%	b>a>c>d	8%	0%
c	**96%**	b>a>d>c	5%	0%
d	1%	c>d>a>b	0%	10%
e	1%	b>a=d>c	**61%**	0%
f	0%	c>a=d>b	0%	4%
		a=b>c=d	0%	5%
		a=c>b=d	0%	14%
		c<d>a=b	0%	**25%**



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Cast your mind back …

- For most of the past 2000 years, people who thought about the sky followed the ideas of Plato and Aristotle and assumed that the moving lights we see were held up on rotating, transparent, crystal spheres.

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What do we see?

- Most of the stars appear to move together, wheeling in an immense circle once a day.
- The sun, moon, and seven "wandering stars" (planets) also show a daily rotation, but in addition, show a drift against the background of stars.
  - The moon moves in a circle through the stars once a month.
  - The sun moves in a circle through the stars once a year.
  - The planets take longer to move and some show a "retrograde" (back and forth) motion over a period of many years.

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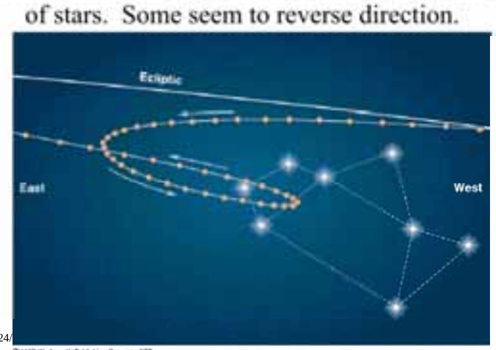
Retrograde Motion

Planets move through the sky across the pattern of stars. Some seem to reverse direction.



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Dueling Models

- Since the motion of the objects in the sky showed a systematic regularity, sailors could use it to keep track of the time.
- In order to get the rotating crystal spheres to produce retrograde motion, the Greeks introduced epicycles" — spheres rolling on spheres rolling on spheres. (Ptolemy c. 150 AD)
- In ~1500, Copernicus proposed putting the sun at the center and making the earth "just one of the planets". This reduced the number of epicycles needed.

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Galileo: Breaking the Crystal Spheres

- In 1594, when Galileo improved the recently invented Dutch telescope and turned it to the skies, he saw a surprise: a planet (Jupiter) had planets (moons) of its own.
- Since these moons appeared to go around Jupiter, there could not be a solid crystal sphere holding it up.

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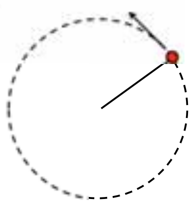
Newton: What holds them up?

- From his detailed studies of motion, Newton knew that the question was not "What holds them up?" but "What pulls them in?"
- Are the moons and planets tied by strings?



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No strings

- Newton's inspiration was to realize that since objects are pulled towards the earth by gravity, so is the moon.
- Perhaps (assuming Copernicus's heliocentric model) the sun pulls the planets by gravity.

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Checking the earth-moon system

- The first thing to see is: does it work for the moon? Is the earth's gravity right to pull the moon in a circular motion around the earth?
- Let's do the math!

$$m\vec{a} = \vec{F}^{net}$$

$$m\frac{v^2}{r} = F^{centripetal} = mg$$

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$$\frac{mv^2}{r} = mg \qquad \frac{v^2}{r} = g$$

$$r = 0.38\times10^9 \text{ m}$$

$$v = \frac{2\pi r}{T} = \frac{2\pi\left(3.8\times10^8 \text{ m}\right)}{\left(28 \text{ days}\right)\left(24 \frac{\text{hr}}{\text{day}}\right)\left(3600 \frac{\text{s}}{\text{hr}}\right)}$$

$$v = 0.99\times10^3 \frac{\text{m}}{\text{s}}$$

$$\frac{v^2}{r} = \frac{\left(0.99\times10^3 \frac{\text{m}}{\text{s}}\right)^2}{0.38\times10^9 \text{ m}} = 2.58\times10^{-3} \frac{\text{m}}{\text{s}^2} = \frac{g}{3800}$$

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A solution

- Newton noticed that the moon was farther from the center of the earth than he was — by (3.8 x 10^8 m)/(2/π x 10^7 m) ~ 60.
- Since $\sqrt{3800} \approx 61$ this is close.
- Knowing that electric forces fall off as the charges get farther apart, he suggested that the gravitational force falls off like $1/r^2$.

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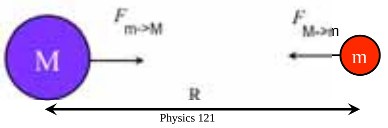
Inventing a Gravitation Law

- What law should we propose? $F = ? / R^2$.
- What goes on top?
- We expect
  - $F_{M\text{->}m}$ proportional to m (from mg)
  - $F_{m\text{->}M}$ proportional to M (from N3)
  - $F_{m\text{->}M} = F_{M\text{->}m}$



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Newton's Law of Universal Gravitation

- All objects attract each other with a force whose magnitude is given by

$$F_{m\to M} = F_{M\to m} = \frac{GmM}{R^2}$$

- G is put in to make the units come out right. (Need N-m^2/kg^2 = m^3/kg-s^2)
- Experimentally, $G \sim 2/3 \times 10^{-10}$ N-m^2/kg^2.

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Gravitational PE

- When we were approximating gravity as constant $W = mg$ we got a PE = mgh.
- What happens if we use gravity as

$$W = GmM/R^2$$

- PE becomes

$$PE = -\frac{GmM}{R}$$

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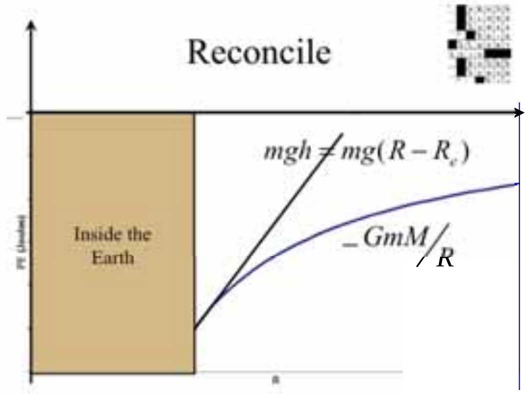
Reconcile



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Implications: New planets in our solar system

- Newton's law of gravitation together with N2 allows us to predict the motion of planets and moons with great accuracy
  (and incidentally to travel to them).
- Small deviations from predicted values hint at previously unknown large objects.
- Leverrier – 1846
  - predicted Neptune and Vulcan in response to discrepancies in the orbits of Uranus and Mercury.

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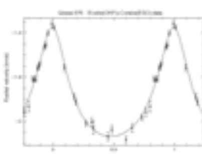
Implications: New planets outside our solar system

- If a star has a large planet (like Jupiter), NUG+N2 imply that they both will orbit about their C of M.
- The star will then appear to wobble in the sky.
- Although we can't see the wobble, the frequency of the light coming from the star shifts slightly with velocity (Doppler shift) and we can see that.
- If we know the star's mass (astronomers infer that from how it shines) we can get info on the size of the planet.



The measured (radial) velocity of a star 15 ly from earth.

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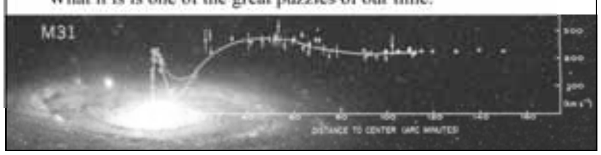
Implications:
A massive object at the galactic center.

- For a variety of reasons, astronomers suspect that the center of many galaxies (ours included) contains an object so heavy and dense that its gravity will not even allow light to escape (a black hole).
- The orbits of stars in the neighborhood of the galactic center are strong evidence for a very small very massive object.
- *http://www.astro.ucla.edu/~ghezgroup/gc/pictures/orbitsMovie.shtml*

Implications:
Galactic rotation and dark matter

- If most of the mass of the galaxy is in the center, we can figure out how the speed of stars orbiting the center of a galaxy should fall off with distance.
- In 1970, a local astronomer, Vera Rubin, showed this didn't work.
- Her work strongly implies the existence of "dark matter" – matter that doesn't emit light spread through the galaxy. What it is is one of the great puzzles of our time.



New Questions!

- As data pours in from new telescopes and new theories are proposed, new questions arise.
  - Is there there lots of invisible matter we can't see in a galaxy (dark matter)? Or does Newton's law of gravitation fail at trans-galactic distances?
  - String theories suggest there may be parallel universes. One way to find if they exist would be to see violations of Newtonian gravitation at distances of millimeters.
- Stay tuned!