Exploring Black Holes

A Unit Based on Force and Motion for Integrated Physics and Chemistry

Part I: NEWS FLASH! Quasars and Fast Stars Inside Galaxies?

Materials for each student:

3 x 5 index card
Student journal

For the class:

PowerPoint, computer, and video projector

Materials for each group (5 groups):

News flashes: cut out each news flash, one for each group.

Duration:

One class period

Begin this first of six activities with a fast write: students respond to a question on a small 3 x 5 index card for two minutes. This is a chance for them to bring their ideas about black holes to the fore of their minds, and give you an idea of what they know.

You may decide to post a giant K-W-L chart (what do I *know*, what do I *want to know*, and what have I *learned*) for students to chronicle their progress through this activity set. This activity gives them a chance to fill up the "K" (what do I know) and the "W" (what do I *want* to know) sections.

Fast write (two minutes)

What do you think are the most important characteristics of a black hole?

News Flashes: Astronomers Astounded by Super-Luminous Objects and Fast Moving Stars Inside the Cores of Galaxies

Break students up into five groups, and give each group a news flash to review. Their job is to review the news flash and present it (with feeling, like the way a news journalist inspires interest in an evolving story) to the class in an interactive way. For instance, student could take a "person on the street" approach to ask members of the class to respond to simple questions based on the news flash: "So, what do you think an astronomer means by loud radio source? A radio turned up too loud, or something shining brightly at radio wavelengths in space?" Let them have some fun.

Let each group review their news flash. They should identify science vocabulary words they know, and words that they do not know.

After student present their news flashes, tell them that they will be learning about new astronomical research that involves large galaxies, like our own Milky Way Galaxy, and black holes. Dr. Karl Gebhardt has put together a new database of the latest research about black holes in giant galaxies and helped build a new website called the Black Hole Encyclopedia. Students will be able to judge whether new black hole claims are science worthy to be included in this new and growing database (part 6). And, they will understand more about why astronomers think black holes exist, and where they might be hiding.

NEWS FLASHES Astronomers Astounded by Super-Luminous Objects and Fast Moving Stars Inside the Cores of Galaxies

1950s - 1960s: Astronomers using telescopes sensitive to radio wavelength light discover small intense sources of radio wavelength radiation. The search is on using visual wavelength telescopes, like those at McDonald Observatory, for the exact location of the "loud" radio wavelength objects. Since the radio telescopes can only give a "ballpark" location for the radio-loud objects, astronomers using optical telescopes are having a tough time finding them.

1960s: One "radio-loud" object has been identified in an optical telescope, thanks to the Moon. As the Moon eclipsed a radio-loud object called 3C-273, its radio signal faded and stopped. This observation helped astronomers calculate the size and exact location of 3C-273. When astronomers looked for 3C-273 with optical telescopes, they could not make sense of what they saw. There data indicated that this object was extremely luminous, as luminous as an entire galaxy, but it looked like a star. It is also the most distant object ever observed. Astronomers called this new kind of object a quasi-stellar radio object, or "quasar." Astronomers and physicists can not yet explain how this quasar radiates so much energy.

1990s: Astronomers continue to discover new quasars at ever increasing distances. Astronomers using the Hubble Space Telescope find stars moving at incredible speeds in the core, or center, of some galaxies. These speeds are incredible because astronomers can not come up with a way to explain them with their current understanding of a galactic core made of stars. Something small but extremely massive, several thousand times the mass of our Sun, seems to best explain the observations of these super-fast stars. But astronomers can not see this super-massive central object. And, stars have never been observed with masses this high. What could it be?

2003: The Sloan Digital Sky Survey detects thousands of quasars and galaxies as it surveys the sky. As a result of this gigantic survey of the sky, astronomers have data for about 120,000 galaxies. This data supports a theory that many galaxies like our own Milky Way and larger have a super-massive black hole in their core. The Sloan Digital Sky Survey also provided astronomers spectrograms of these galaxies, which showed that the central black holes are getting bigger, and making the cores of these galaxies brighter. Sometimes, the core grows brighter than the whole galaxy.

2004: Dr. Karl Gebhardt, an astronomer at the University of Texas at Austin, launched an effort to collect information about galaxies with possible black holes in their cores into one database. This database will help other astronomers compare these galaxies and find relationships between them. Astronomers may submit their own black hole candidates to Gebhardt and his team to be evaluated and possibly included in this growing database of black hole candidates.

PowerPoint: Use your computer running PowerPoint and video projector to show this image.

Tell students that Markarian 205 is a quasar, and NGC 4319 is a galaxy.

Ask students which object in this Hubble Space Telescope image do you think is the quasar? Which one is the galaxy, NGC 4319?

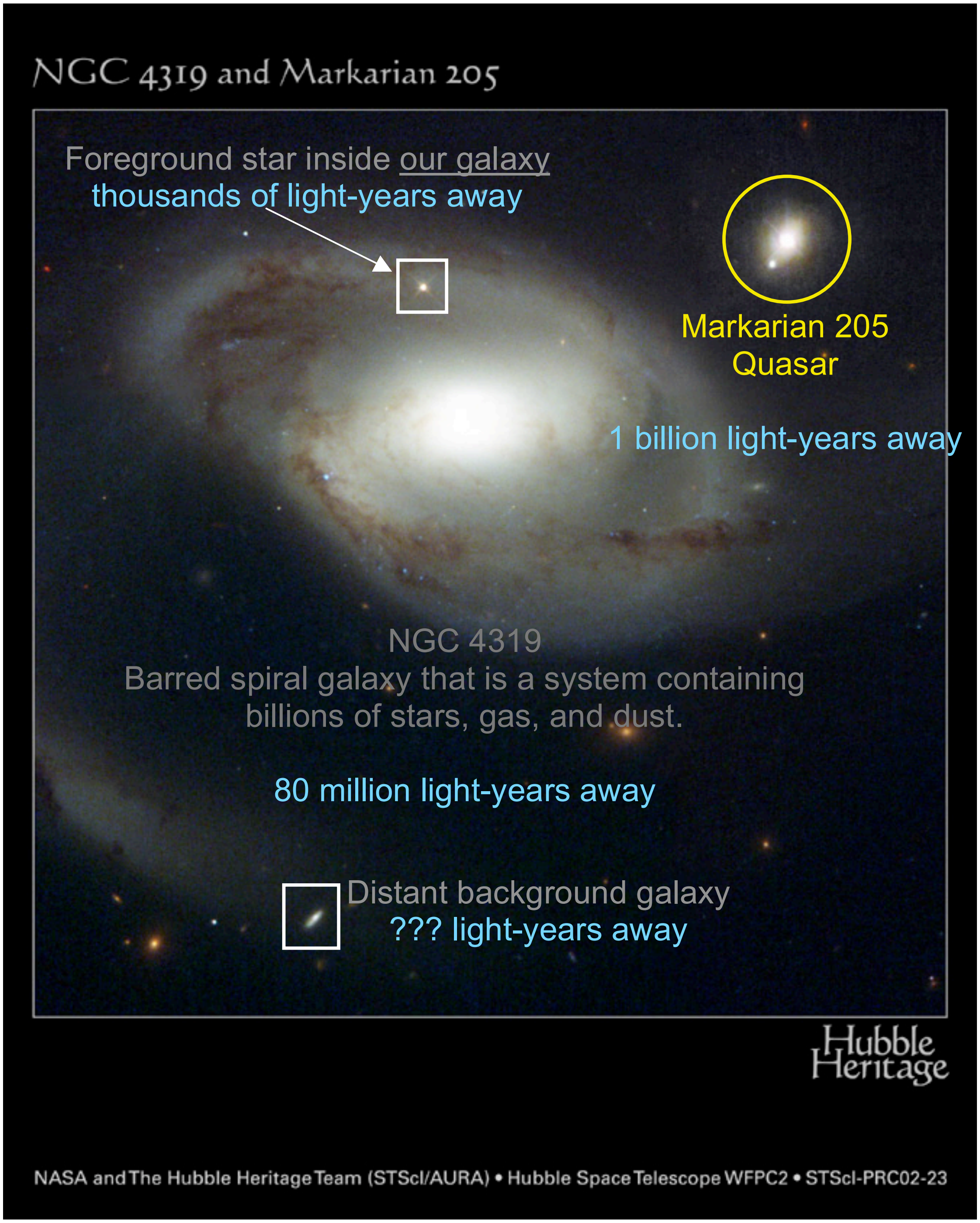
Special thanks to NASA, The Hubble Heritage Team (STScI/AURA), and R. Knacke (Penn State Erie)
http://hubblesite.org/newscenter/newsdesk/archive/releases/2002/23/image/a

PowerPoint: Advance the PowerPoint to the next frame. Point out the quasar and galaxy.

To help students make a distance comparison, ask them to express 1 billion in terms of millions (1,000 million) or in terms of thousands (1,000 x 1,000 thousand). Point to the centers of the galaxy and quasar and ask them to compare the brightness: they are nearly the same! That means the quasar must be extremely luminous in order to appear as bright as the nearby galaxy, like a distant car headlight compared to a nearby candle.

Help students contrast the concepts brightness (how much light our eyes or telescope collects) and luminosity (an intrinsic property, how much light an object emits – like a light bulb).

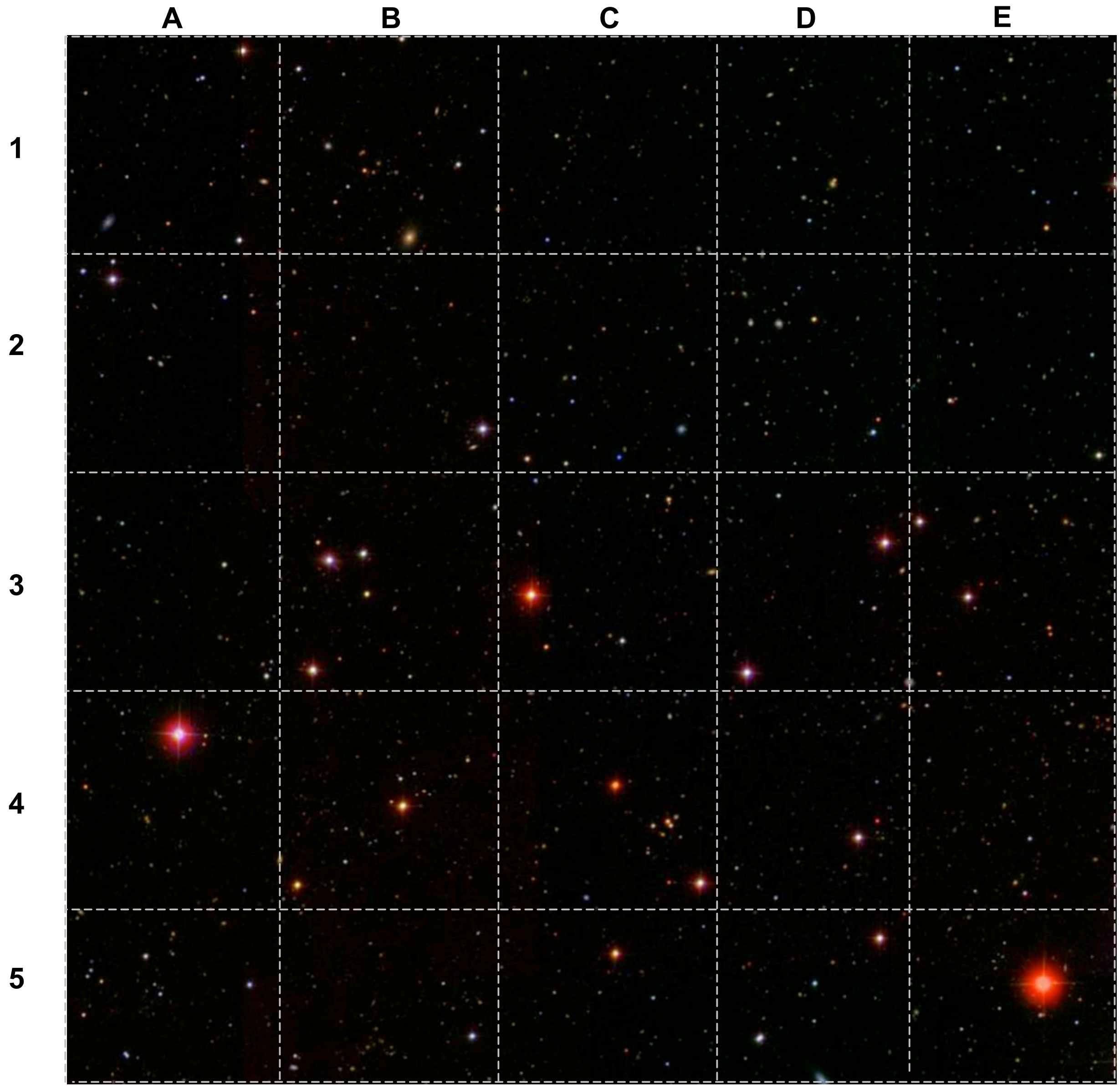
See http://heritage.stsci.edu/2002/23/caption.html for a well written explanation and more information.



Find the Quasar

PowerPoint: Show students this image and tell them that one of these objects is quasar *3C-273*.

The rest are stars in our galaxy or other galaxies.

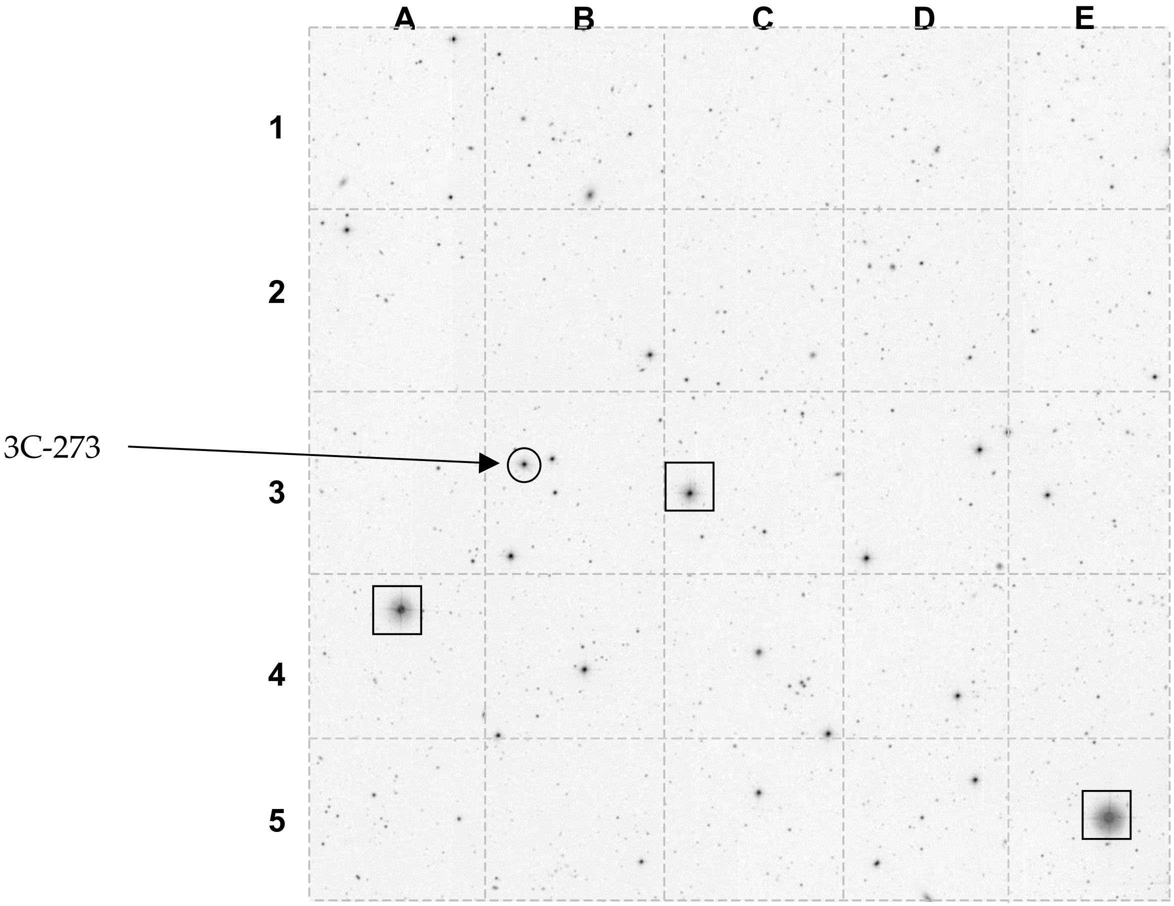


Special thanks to the Sloan Digital Sky Survey http://www.sdss.org/

Find the Quasar

Tell students that one of these objects is quasar *3C-273*. The rest are stars in our galaxy or other galaxies.

This is a negative image: bright objects, like stars, are dark. Astronomers like to view these types of images because bright objects show up easily.



Special thanks to the Sloan Digital Sky Survey http://www.sdss.org/

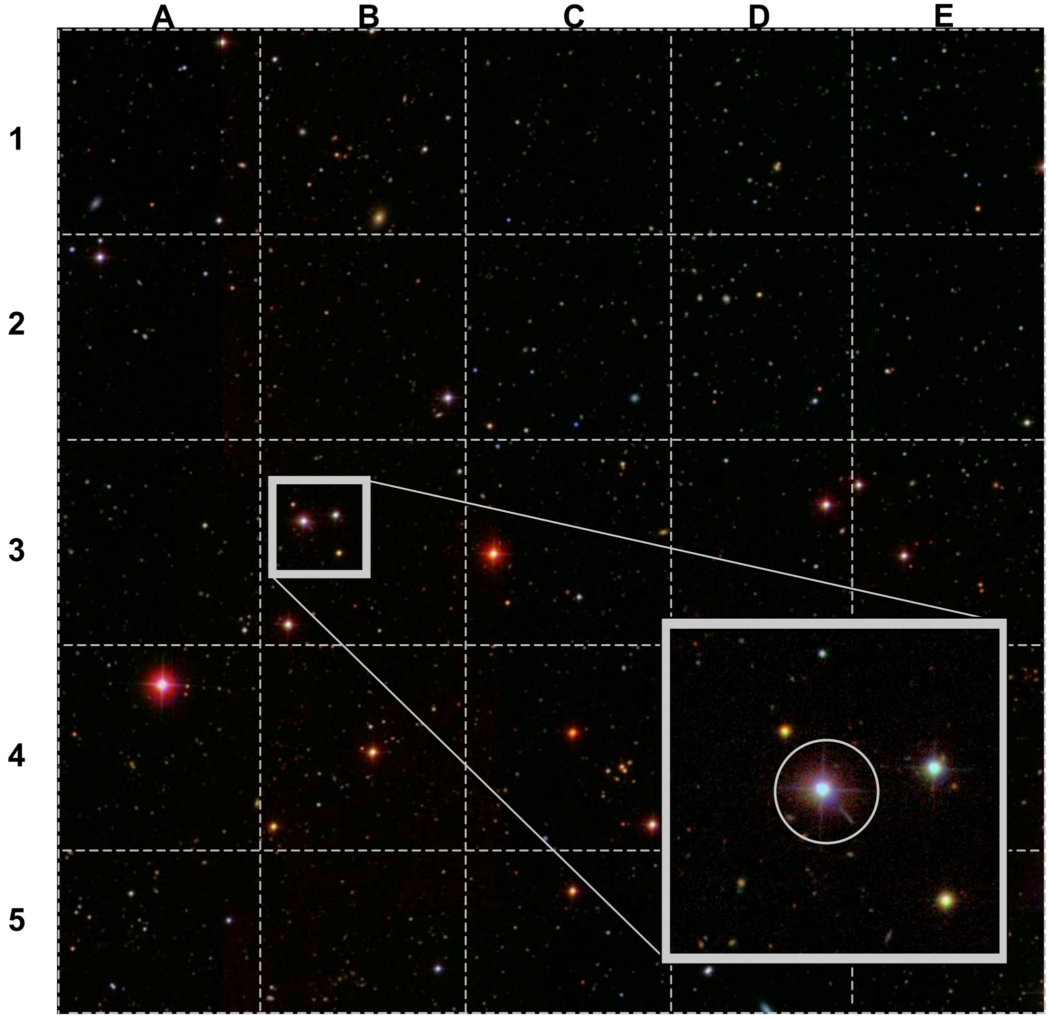
Questions: Respond in your journal

1. Based on this picture, can you tell which objects are nearby and which objects are far away? Explain.
NO! Stars are not all equally luminous. Some are hundreds of thousands of times more luminous that the Sun, while most stars are about as luminous or less than the Sun. Students may say that the brightest (darkest in this negative) are closer.

2. Which one do you think is the quasar: something that looks like a star and radiates more light than an entire galaxy? Explain.
Most students pick the brightest objects in D4, A4, or C3. The point here is to struggle a bit, just like the astronomers, to realize that more information is necessary to pick which object is the quasar.

Location of the Quasar

PowerPoint: Show students this frame.



Special thanks to the Sloan Digital Sky Survey http://www.sdss.org/

The quasar 3C-273 is circled in the center of the box. The four spindles, like a plus shape (+), are diffraction effects from the telescope. But the "tail" at the 4 o'clock position is real – it's a jet of super-hot plasma light-years in length.

Astronomers observed the visual spectrum of 3C-273 to calculate its distance and luminosity. The strong absorption/emission features of hydrogen (Balmer series) were red-shifted by the Doppler effect, because of the vast distance and expanding space between our galaxy and the quasar. By measuring this shift and using Hubble's Constant, astronomers calculate the distance to the quasar.

See Hubble's Constant: http://hubblesite.org/reference_desk/glossary/cosmology.shtml
Background: http://hubblesite.org/newscenter/newsdesk/archive/releases/1999/19/text/

PowerPoint: The next slide shows 3C-273 and Mrk 205 together.

Read, Listen, and Review

Have students listen to and read the StarDate radio program about 3C-273: *The First Quasar* April 6, 2001.
http://stardate.org/radio/program.php?f=detail&id=2001-04-06
PowerPoint: The whole class can read the text in the PowerPoint.

The First Quasar

The Moon lines up with one of the most famous objects in the sky tonight – a quasar known as 3C 273 in the constellation Virgo. But in the early 1960s, there was an even better alignment – the Moon eclipsed the quasar, making a bit of astronomical history.

At the time, 3C 273 was known as a "radio star." Though astronomers could detect it with radio telescopes, they couldn't pinpoint its location well enough to SEE it with *optical* telescopes.

But that changed the day the Moon passed between the radio star and Earth, blocking its radio signals and allowing astronomers to pinpoint its location. With this information, they could find the object with optical telescopes for the first time.

Even then, they couldn't quite fathom what they saw. Photographic plates showed only an inconspicuous blue star. But when astronomers split the star's light into its individual wavelengths, they found that it was unlike any known star, galaxy, or nebula. Further study eventually revealed that it's billions of light-years away, which means it must be incredibly bright. It's also small, which means its energy source must be incredibly powerful.

Today, astronomers believe that 3C 273 and the thousands of other known quasars are monstrous black holes encircled by disks of gas. As gas spirals into the black hole it's heated, so it glows brightly -- bright enough to see across most of the universe.

Questions: Respond in your journal

1. Why do you think quasar 3C-273 was such a surprise to astronomers?

2. Why do you think astronomers explain observations of quasars using a model of a black hole?

Part II: What is Escape Velocity?

Materials for each experiment group:

6 meter sticks for the track and ramp, masking tape, big ball bearing (at least 1-cm diameter), stopwatch
Books to prop up the ramp
1 meter stick to measure vertical height
Calculator

Cooperative group members:

Timer Measures the time the ball takes to move one meter before climbing the ramp.	**Data recorder** Records the time and notes the final height of the ball.
Roller Gives the ball a push to accelerate it to a speed.	**Height watcher** Watches the ball travel up the ramp and confirms that the ball reaches the target height.

Read the following from the Black Hole Encyclopedia *A Daring Journey* by Dr. Gregory Shields:

> Isaac Newton's theory of gravity led to early concepts of a black hole in the late 1700s. Gravity's pull on an object grows weaker as the distance increases. If a space probe or other projectile is launched from the surface of a massive body with sufficient speed, it will fly off into space forever. This minimum speed is called the **escape velocity**.
>
> In Newtonian gravity, the escape velocity from a spherical body depends on its size and mass. As the size decreases and the mass increases, escape velocity goes up. For the escape velocity to equal the speed of light (186,000 miles (299,000 km) per second), nature requires a certain size for a given mass. If an object contracts to this critical size, light can no longer escape from its surface to the distant universe. This is the essence of a black hole.

Ask students to respond to the following situations related to escape velocity:
1. Does the Earth have an escape velocity? What about the Moon?
Accept all responses.

2. Compare Earth and the Moon. Would you be able to jump higher on the Earth or Moon?
*You can jump higher on the Moon. Your mass remains constant, but your weight (**a force that depends on your mass and the Moon's mass**) will change because the Moon's mass is much smaller than Earth's mass.*

3. What about throwing a ball, like a football or basketball? Where could you throw it farther: on the Moon or Earth (inside an airtight gymnasium at standard temperature and pressure)?
*On the Moon. The ball weighs less. But when you throw the ball**, it feels just as hard to throw as it does on Earth – that's inertia, which is tied to the mass of the ball.***

4. So, which body has the greatest escape velocity: the Earth or Moon?
Earth: 11.2 km/s. The Moon's escape velocity is 2.4 km/s.

5. If you were on the Moon's surface, and could throw a ball so that it left your hand at 3 km/s, would it fall back to the Moon?
No. It is traveling fast enough to escape the Moon's gravity.

Experiment: What is Escape Velocity?

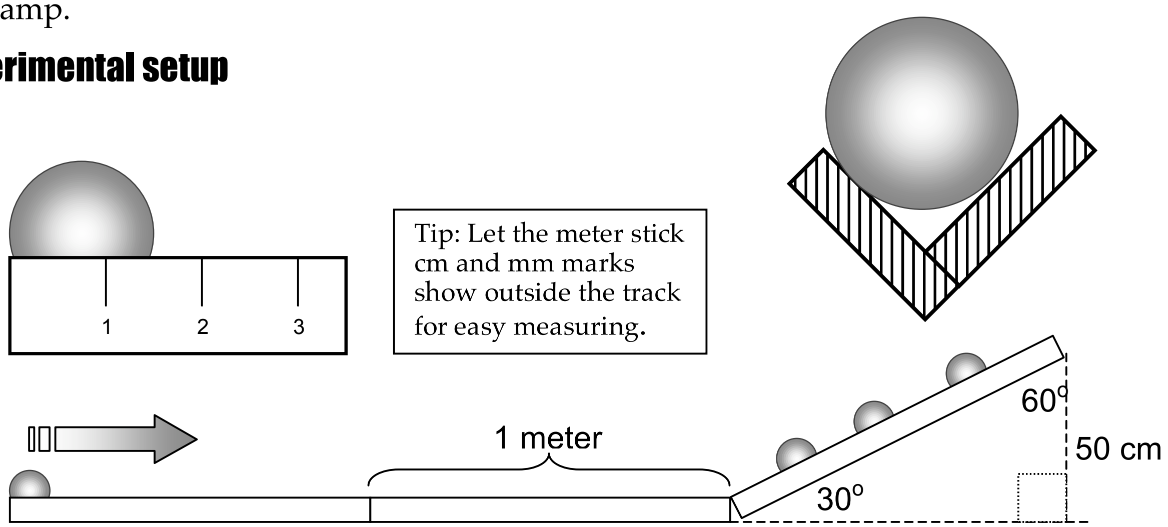
Begin

Divide students up into cooperative groups. Tell them that they will continue their exploration of escape velocity with an experiment.

Experiment summary

Students roll balls up a ramp to find how fast the ball must go in order to climb 10, 20, and 40 centimeters *vertically*, not along the ramp. Student calculate the speed of the ball by using a stopwatch to measure the time the ball takes to move along a known distance before climbing the ramp.

Experimental setup



Tip: Let the meter stick cm and mm marks show outside the track for easy measuring.

Ball	Ramp & Track	Ramp angle	Books	Tape or putty
steel ball bearing at least 1 centimeter in diameter	meter stick pair in an "V". Minimum of 6 meter sticks: 2-meter track, 1-meter ramp.	20-30 degrees from the floor. The end of a 1-meter ramp will be 50 cm above the floor. (30-60-90 right triangle)	to prop up the ramp	hold the ramp and track in place.

Control of variables

During their experiment, students should keep these variables and conditions constant:

1. The known distance to calculate the speed.
2. The ball.
3. The length of the ramp.
4. The angle of the ramp.

Confounding variables

Friction: use a heavy steel ball bearing so that air drag and friction between the ball and track are small compared to the inertia of the ball.

What to expect

The graphs should look about the same from group to group. Differences will be due to the confounding variables and natural human experimental error.

No matter what the mass of the ball bearing is, the velocities will be about the same to get vertically up to 10, 20, and 40 centimeters. Ball bearing or Space Shuttle, the escape velocity for each is the same.

Analysis and Prediction

How does the minimum speed change if you increase the height the ball travels?

Compare the minimum escape speeds for a ramp height of 10, 20, and 40 cm. Student can pick a fourth height. Plot your data on the graph.

How fast should the ball travel to climb all the way up the ramp?

Using your plot, predict how fast the ball must go to climb to the very top of the ramp. Then, *measure* the ball speed so that the ball climbs to the top of the ramp. How accurate was your prediction? This speed is the escape speed for the ramp.

Ball Height	Ball speed	Comments or Notes

Optional Part III: Escape velocities in our Solar System

If you wanted the ball to escape Earth's gravity from Earth's surface, the ball must travel 11.2 kilometers per second. That would be the equivalent of raising the ramp as high as you can imagine from the surface of the Earth. Then you would accelerate the ball to a velocity of 11.2 km/s.

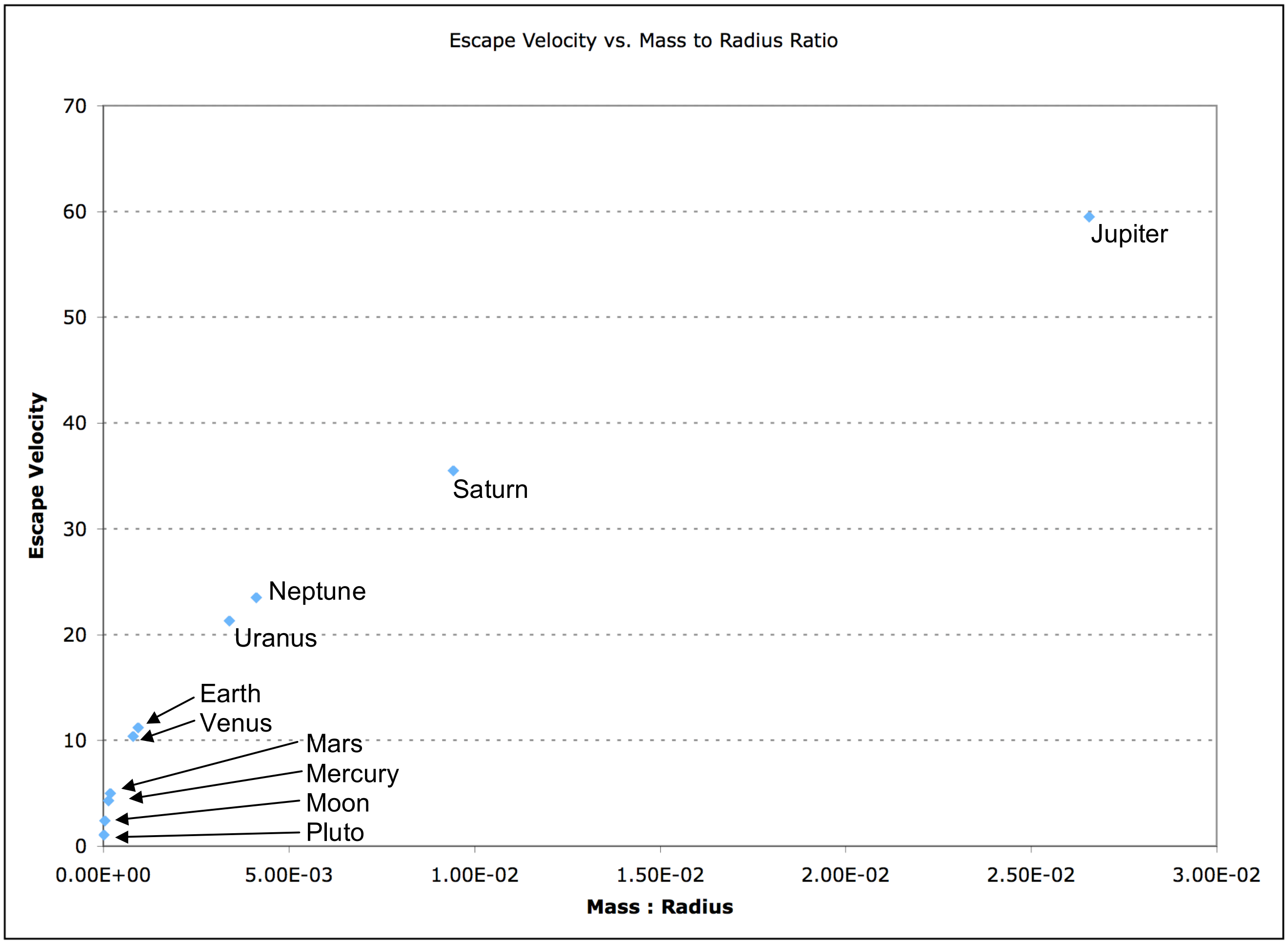
Here are the escape velocities of other planets and our Moon in the solar system:

Planet	Mass 10^{24} kg	Radius of the planet or moon km	Mass Ratio $\frac{Mass}{Radius}$	Escape Velocity from the planet/moon surface km/s
Mercury	0.33	2,440	0.0533	4.3
Venus	4.87	6,052	0.815	10.4
Earth	**5.97**	**6,377**	**1**	**11.2**
Moon	0.073	1,738	0.0123	2.4
Mars	0.642	3,397	0.107	5.0
Jupiter	1899	71,492	317.8	59.5
Saturn	568	60,268	95.2	35.5
Uranus	86.8	25,559	14.5	21.3
Neptune	102	24,764	17,1	23.5
Pluto	0.0125	1,195	0.0021	1.1

What about the Sun?

Mass 10^{24} kg	Radius km	Mass Ratio	Escape Velocity km/s
1,989,100	696,000	333,000	617.6

National Space Science Data Center
http://nssdc.gsfc.nasa.gov/planetary/factsheet/index.html



What kind of algebraic relationship do you expect between the escape velocity and the mass to radius ratio?

V_{escape} and $\frac{Mass}{Radius}$

Escape velocity equation: $V_{escape}^2 = \frac{2GM}{R} = (2G)\left(\frac{M}{R}\right)$ $V_{escape} = \sqrt{\frac{2GM}{R}} = \left(\sqrt{2G}\right)\left(\sqrt{\frac{M}{R}}\right)$

V_{escape}:	escape velocity
G:	Gravitational constant = 6.67 x 10^{-11} N•m^2/kg^2
M:	mass
R:	radius measured from the center of mass

Note: for the plot of escape velocity vs. mass to radius ratio, mass is in units of 10^{24} kilograms. So, Earth has a mass of 5.97; the Moon 0.073, Jupiter 1899, Pluto 0.000010.

National Space Science Data Center http://nssdc.gsfc.nasa.gov/planetary/factsheet/index.html

Part IV: Do objects exist with a mass and radius so that its escape speed = speed of light?

Materials for each student group:

Student journal, calculator, pencil, metric ruler (to help them plot points).

Begin with a quick dialog:

We have worked with an experiment and talked about Earth having an escape velocity of 11.2 km/s. So, if I could throw a baseball up to the sky so that it is moving at 11.2 km/s, what would happen?
It would move away from the Earth, and never stop. It would NOT orbit the Earth (too fast).

What would happen to the escape velocity if we could squish the Earth, and make it much smaller?
The escape velocity would increase. The force of gravity depends directly on mass and inversely with radius (or distance from the center of mass).

Write this equation on the board: $R = \frac{2GM}{V_{esc}^2}$ can also be expressed as $V_{esc}^2 = \frac{2GM}{R}$

V_{esc}: Escape velocity (m/s)
G: Gravitational constant = 6.67×10^{-11} N•m^2/kg^2
M: Mass of material inside the radius (kg)
R: Radius (m)
c: Speed of light 3×10^8 m/s

Discuss the relationship between radius, mass, and escape velocity. Try "what would happen if…" with the variables of radius, mass, and escape velocity. Try hiding the constants (2G) so that students can focus on just the variable relationships.

Then ask "So, what would an object look like if its escape velocity was the speed of light?"

Have students work in groups to calculate radii where escape velocity is the speed of light and plot their results.

Summarize your calculations in the table. Make a plot mass verses radius where $V_{esc} = c$.

Name	**Mass**	**Radius**	**Radius** Where $V_{esc} = c$
Earth	5.97×10^{24} kg	6,390 km	
Jupiter	1.9×10^{26} kg	71,400 km	
Sun	2×10^{30} kg	696,000 km	

Interesting objects

Name	**Mass**	**Solar Masses**	**Radius**	**Radius** Where $V_{esc} = c$
Sun	2×10^{30} kg	1	696,000 km	
White dwarf	2.8×10^{30} kg	1.4	6,000 km	4.1 km
Neutron star	6.0×10^{30} kg	3	20 km	8.9 km
Large star	2×10^{31} kg	10	7×10^{6} km	
Object A	2×10^{32} kg	100	?	
Object B	3×10^{32} kg	150	?	
Object C	4×10^{32} kg	200		
Object D	1×10^{33} kg	500		

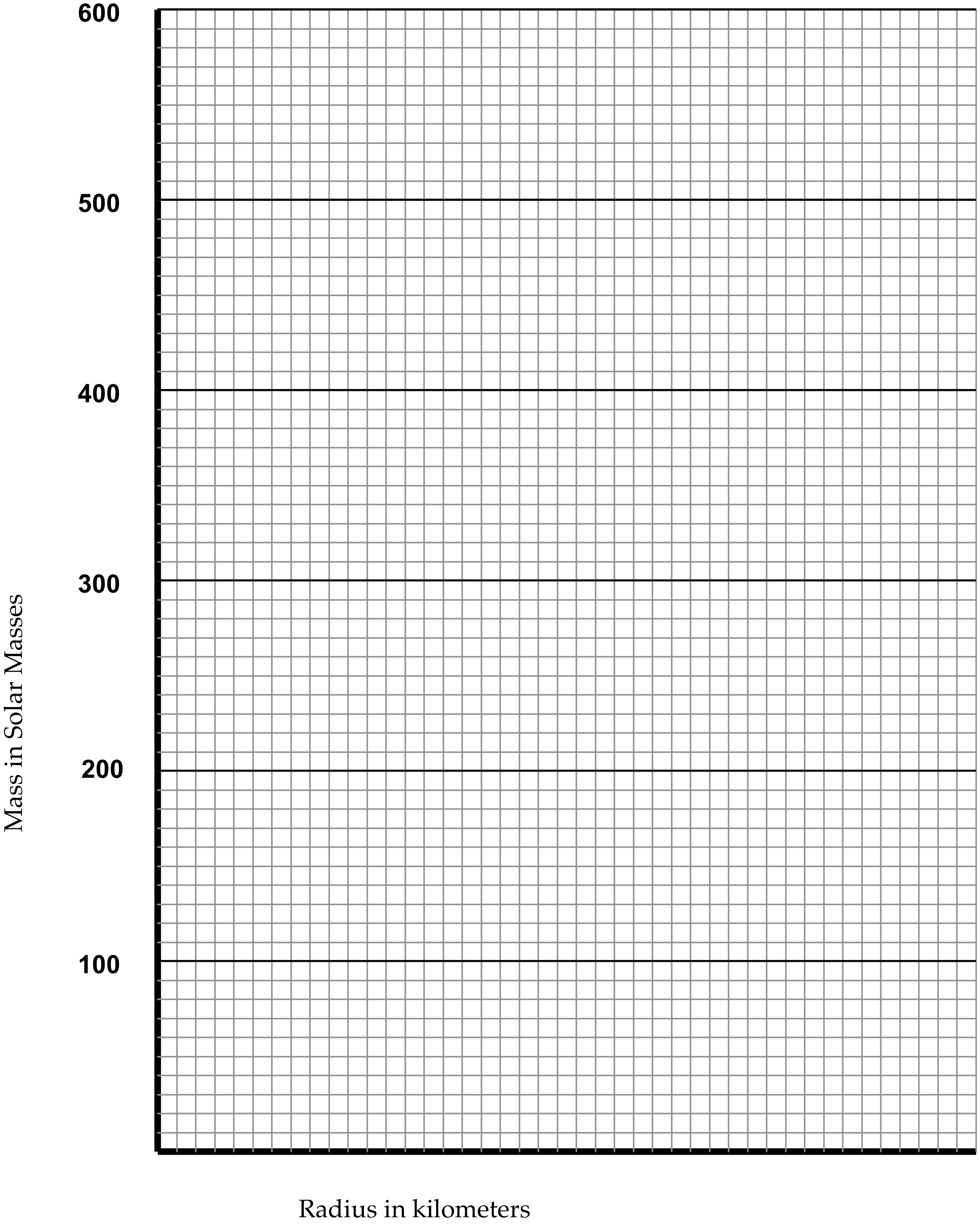
What is a Black Hole?

Tell students that if all the mass of Object A through D were packed inside the radius where $V_{esc} = c$, these objects would be black holes. In fact, the same is true for any of these objects.

Students are ready to read, enjoy, and get a better physical understanding of black holes with the help of the following article from the Black Hole Encyclopedia, "What is a Black Hole?".

Black Hole Encyclopedia: "What is a Black Hole?"
http://blackholes.stardate.org/basics/basic.php?id=2

Mass verses radius where $V_{esc} = c$



Optional: White Dwarfs, Neutron Stars, and Black Holes – Oh My!

Most stars, like our Sun, eventually become white dwarfs. Only the rare massive stars, more than 8 or 10 times the mass of our Sun end up as neutron stars after blowing most of their material away in a supernova.

Neutron stars represent matter packed together at about the maximum density. They are made of neutrons – a sphere of neutrons the size of a small city packed together with the density of an atomic nucleus. No one is quite sure how massive neutron stars can get. But there is a limit for white dwarfs: 1.44 solar masses. Astronomers call this limit the **Chandrasekhar limit**, named after Subrahmanyan Chandrasekhar.
http://hyperphysics.phy-astr.gsu.edu/hbase/astro/whdwar.html

Astronomers have observed neutron stars and white dwarf stars, and calculated their masses. These objects have been observed in systems with companion stars. By observing and measuring the motion of the companion stars or other orbiting matter, astronomers calculate the mass of the white dwarf or neutron star. They can use Newton's Laws because the motion of the orbiting objects is well below the speed of light.

Astronomers have also observed stars with masses greater than 20 solar masses. Although these stars end up exploding as a supernova, some of the mass is left over from the star's core. Astronomers think that if more than 2 to 3 solar masses of material is left over in the core, it will collapse under its own weight. The force of gravity will crush the core into something even smaller than a neutron star – smaller than the radius where $V_{esc} = c$.

$R_{core} \leq \frac{2GM_{core}}{c^2}$ What happens when the core's radius is less than the radius where $V_{esc} = c$?

No one is quite sure. Astronomers have not observed this event. But they do use a mathematical model based on the physics we do understand to explain quasars, and fast moving stars inside the cores of large galaxies.

But that is black hole. It's an object (it has mass) with an escape velocity equal to or greater than the speed of light. The radius where the escape velocity is the same as the speed of light is called the *event horizon* – the radius of no return. No information or object may return from the event horizon, because nothing travels through space faster than light.

Black Holes – How Big Do They Get?

Ask students about their plots of mass verses the radius where $V_{esc} = c$:

1. Do you think there is a limit to how massive black holes can get?
There appears no limit to how massive black hole can become. When astronomers talk about the size of a black hole, they are referring to the radius of its ***event horizon****, where* $V_{esc} = c$.

Black Hole Encyclopedia: "Structure of a Black Hole"
http://blackholes.stardate.org/basics/basic.php?id=5

Questions about "Structure of a Black Hole"
1. What is the key physical property of the event horizon?
The event horizon is the point of no return, where the escape velocity is the speed of light. All the mass of the black hole is inside the event horizon.

2. Could a spacecraft orbit a black hole?
Yes. As long as you stayed far away from the event horizon, your spacecraft could safely orbit the black hole. Just make sure your spacecraft has enough fuel to accelerate you to the escape velocity for your distance from the black hole!

Black Hole Encyclopedia: "Birth of Supermassive Black Holes: Battle of the Bulge"
http://blackholes.stardate.org/basics/basic.php?id=9

PowerPoint: Show the frames with the Andromeda Galaxy so that students can see the parts of the galaxy (disk, bulge, core).

Questions about "Birth of Supermassive Black Holes: Battle of the Bulge"
1. Where do astronomers think super-massive black holes lie?

2. Where is the bulge of a galaxy?

3. How super is super-massive – what is the mass of these big black holes?

4. What are the observation clues that strongly support this model of super-massive black holes?

5. How do you think a super-massive black hole could form?

Part V: Why do Astronomers Think that Black Holes Exist?

How would YOU find a black hole?

Ask students how they think astronomers could detect a black hole: could astronomers detect them directly or indirectly? What evidence do students think astronomers are looking for?

Show students the PowerPoint slides of hurricane Katrina compared to a galaxy. Read the following from the Black Hole Encyclopedia article *Seeing the Unseeable:*

They [Astronomers] can also deduce the presence of a super-massive black hole by measuring the velocities of clouds of gas that orbit the black hole. The gas emits radio waves and other forms of energy. By measuring changes in the speed of the gas clouds toward or away from Earth, astronomers measure their speeds. Because gas usually follows circular orbits, it is easier to use them to measure the mass of the black hole they orbit.

Ask students "Have you watched water spiral down a drain?"

Demonstration:

Fill up a sink with water, then let students watch the water go down the drain. As it starts to spiral down, remind students that liquids and gases behave the same way. Scientists sometimes refer to liquids and gases as **fluids.**

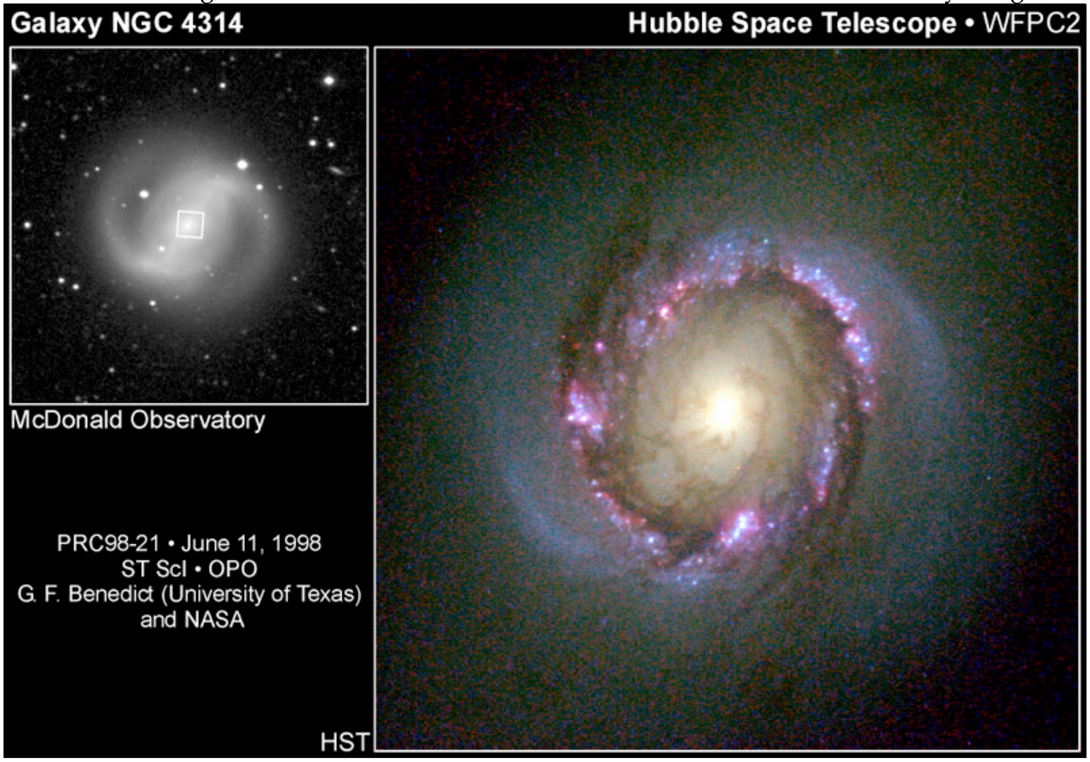
Then ask "What about a tornado or hurricane? How do the gases move in these storms?"

NOAA Satellite and Information Service http://www.nnvl.noaa.gov/

PowerPoint: Ask students to compare hurricane Katrina and galaxies.

Hurricane Katrina making landfall over Louisiana

Core of a barred spiral galaxy, NGC 4314.
The HST image shows the core, which is boxed in the McDonald Observatory image.



Credits: G. Fritz Benedict, Andrew Howell, Inger Jorgensen, David Chapell (University of Texas), Jeffery Kenney (Yale University), and Beverly J. Smith (CASA, University of Colorado), and NASA

PowerPoint: show student the picture of M87 and the Hubble Space Telescope Imaging Spectrograph (STIS) spectrogram. The spectrogram shows the Doppler effect on light emitted by gas, near the core, moving toward (blue) and away (red) from us. The green part of the spectrogram represents gas moving *across* from our perspective.

Questions: Respond in your journal:

1. What do the hurricane and galaxy have in common?

2. How is the gas distributed?

3. Where do you think the gas is moving the fastest?

4. What are the biggest difference between the galaxy and hurricane?

Read and Review

Ask students to read this article from the Black Hole Encyclopedia. Tell them to underline or highlight science vocabulary words that they do not understand. After reading this article, start a dialog to address the new vocabulary and connect to what they have learned so far. The KWL chart will help you and students keep track of your journey so far.

Dialog questions (examples):
How do you think the stars and gas are moving (orbiting) in the core (within the bulge) of a galaxy?

How do you think future information and engineering technology can help astronomers improve their theoretical models?

PowerPoint: show students the black hole movies in the last frame of the PowerPoint.

Black Hole Encyclopedia: *Seeing the Unseeable*

Because a black hole is both massive and compact, it exerts a strong gravitational pull on the material around it. Astronomers can deduce the presence of a super-massive black hole in the core of a galaxy by measuring the velocities of stars that orbit the black hole. A more-massive black hole will accelerate nearby stars to greater speeds, so the velocities of stars can reveal not only the presence of a black hole, but its mass as well.

They can also deduce the presence of a super-massive black hole by measuring the velocities of clouds of gas that orbit the black hole. The gas emits radio waves and other forms of energy. By measuring changes in the speed of the gas clouds toward or away from Earth, astronomers measure their speeds. Because gas usually follows circular orbits, it is easier to use them to measure the mass of the black hole they orbit.

Astronomers use these same basic techniques to discover stellar-mass black holes (those that are a few times as massive as the Sun).

Many star-mass black holes are members of binary systems, which means they have companion stars. In a binary that contains a black hole and another type of star (one that produces visible light or other forms of energy), the orbital speeds of the two component stars is much greater than in a system with two "normal" stars (stars that are similar to the Sun). Measuring the orbital speeds of the two components in a binary system, along with the distance between the stars, reveals the system's total mass. Using other techniques, astronomers can determine the mass of the luminous companion. By subtracting that from the system's total mass, they can determine the mass of the dark companion, which reveals whether it is a black hole or a less-dense object like a neutron star. This technique is like the one that astronomers use to deduce the masses of planets in solar systems other than our own.

In addition, many black holes are encircled by disks of super-hot gas, called accretion disks. In the case of a star-sized black hole, the gas usually comes from a nearby companion star; the black hole's powerful gravity pulls gas off the surface of the star. In the case of a super-massive black hole, the source is large clouds of gas in the crowded core of a galaxy, or stars that pass close to the black hole and are torn apart by its gravitational pull. As the gas spirals into the black hole, it forms a wide, flat "accretion disk." The gas moves faster and faster as it spirals closer, so it's heated to millions of degrees. At such temperatures, the gas radiates most strongly in ultraviolet or X-ray wavelengths. These wavelengths are blocked by Earth's atmosphere, so only telescopes in space can detect them.

In many cases, these telescopes can measure the speed of the gas at different distances from the black hole, which provides a good measurement of the mass of the central object, which provides a high level of confidence that the object is a black hole.

In other cases, though, the object is so small and distant that telescopes cannot see details in the accretion disk. In these cases, astronomers deduce the source of the X-ray or ultraviolet energy from the overall characteristics of the energy. This method has yielded detections of thousands of possible black holes in many different galaxies.

But this technique doesn't provide enough details to give an accurate measure of the black hole's mass and, in some cases, whether the systems actually contain black holes; different types of objects could produce the X-ray or ultraviolet energy. Furthermore, since astronomers only measure the total X-ray energy, they have to rely on theoretical models of how those x-rays are produced to determine a black hole mass. Thus, it is not a direct measure of the mass. Confirmation of these possible black holes may await future orbiting telescopes that can see the universe with greater clarity than current instruments.

Finally, if a star or galaxy passes directly behind a black hole as seen from Earth, the black hole's gravity will distort and amplify the light of the background object. Astronomers are conducting several searches for black holes using this technique. The same technique can lead to detections of planets in distant star systems.

Part VI: They Might be Black Holes

Materials for each student group:

Black hole claims
Black Hole Database
Helpful plots of black holes in the Black Hole Database
Evaluation rubric
Optional: computers and Internet browsers to view the Black Hole Encyclopedia black hole directory http://blackholes.stardate.org/directory/

Getting Ready

Divide students into cooperative groups with no more than 4 students per group. Tell students that they are astronomers working with Dr. Karl Gebhardt. They are in charge of a new astronomical database of black holes. Each group will evaluate a set of claims about systems other astronomers think contain black holes. Some of these systems may become part of the black hole database. But how each group decide?

Main driving question: What evidence do you think supports a conclusion that a system contains a black hole?

First Task: Review systems that most likely contain black holes
Students in each group should review the database and look at the plots. They should ask themselves:

1. What do these accepted candidates have in common?
2. How should we determine if a new claim is a good black hole candidate, or should be rejected?

Second Task: Make an evaluation instrument
Students make an evaluation rubric based on their review and their new understandings of the properties of black holes. Assign one member of each group to write down the group's rubric for evaluating systems that astronomers suspect contain black holes.

Observations or calculations that support a system containing black holes

Observations or Calculation	Little support	Significant support	Strong support

Third Task: Evaluate the claims
Several groups of astronomers have been investigating systems that they think contain black holes. Each group will evaluate the claims, and decide if the evidence is strong enough to include these systems in the database of black holes. If the group rejects the claim, they must explain in a letter to the astronomer.

New Black Hole Candidates

To be evaluated by the Black Hole Database Committee

Lead Astronomer: Dr. Starr Brite
Using the Harlan J. Smith telescope at McDonald Observatory, we observed the bulge of a spiral galaxy, NGC 314159. Although the galaxy's bulge was not very bright, we measured a high velocity for stars of about 350 kilometers per second inside the bulge. Perhaps thick masses of dust are blocking the visible light from reaching the telescope. The bulge appears extremely compact and organized. We would like to do follow up observations, which may support our hypothesis that a 10^4 to 10^5 solar mass black hole lies in the bulge of this galaxy.

Lead Astronomer: Dr. Ima Stronomer
We have detected a black hole with a mass of 10^9 solar masses. The bulge of its host galaxy is extremely bright, which could only come from a compact and powerful source like a black hole. Although the velocity of luminous material is low (50 km/s), we think that the black hole is so large that our instrument can not record the innermost and fastest moving matter. The matter that our instrument can record is located far away from the black hole, so is moving more slowly than other claims reported in the Black Hole Database. We are considering follow up observations that may further support our claim.

Lead Astronomer: Dr. Sol Faraway
In our survey of spiral galaxies, we observed a peculiar galaxy with an extremely bright bulge. Further spectroscopic observations showed that the bulge material is orbiting a central object at about 250 km/s. To rule out intervening foreground objects, like a nearby star, we checked the astronomical database Set of Identifications, Measurements, and Bibliography for Astronomical Data (SIMBAD) for other objects at the galaxy's coordinates. No other objects appear in the foreground. The bulge appears well organized. We think the central object is a black hole with a mass of 10^9 solar masses.

Lead Astronomer: Dr. Cal Q. Laater
Our observations suggest that a 3×10^6 solar mass black hole is in the central core of the elliptical galaxy NGC 271828. We measure high velocities of gas and dust of 275 km/s. This elliptical galaxy shows no unusual brightness changes from end to end, most likely due to dust and gas scattering light from the core.

Lead Astronomer: Dr. Usee Themun
Recent observations with our new instrument on the McDonald Observatory 2.7-meter Harlan J. Smith telescope show strong support for a massive 5×10^5 solar mass black hole in the bulge of NGC 20051205, a spiral galaxy. Our instrument could measure the velocity of bulge material orbiting at 100 km/s. We observed the galaxy along its spiral disc edge, so we could not see the bulge well. We strongly suspect that follow up infrared observations will show strong far infrared emission in the bulge. X-ray observations may show extremely energetic activity from the bulge.

Hypothetical Black Hole Candidate Claims Rubric

How an astronomer thinks

Clues / Observations	No Way	Maybe – needs more observing time	Very likely
Motion of luminous matter (stars, gas, dust in IR)	Slow moving Little organization of orbits		Calculated central mass does not fit a model of a dense star system.
Distribution of luminous matter	Sparse		Concentrated around a center Disc or spherical distribution Bright center
Accretion disc	No disc		Well organized disc
Jets	None		Distinct structure
Visible light	Star or star system like luminosity		Very distant Low apparent brightness Extremely luminous Small – too small to be system of stars
X-ray emission	none	Some	Strong Emission from jets
Infrared emission	Weak	Some	Strong in a small region
Radio emission	Some or none	Some	Strong Emission from jets

Students' rubrics will be simpler.

The database does not list information like accretion discs, X-ray emission, IR emission, etc.; but, these are clues about what else might be going on inside these systems.
New space telescopes, like the Spitzer Space Telescope and Chandra X-Ray Observatory can see what optical telescopes can not. Astronomers need coordinated observations across the whole electromagnetic spectrum to better investigate these systems.

Additional resources

Super-massive black hole directory: Let students explore the black hole directory of super-massive black holes on the Black Hole Encyclopedia website (http://blackholes.stardate.org/directory/).

StarDate Guide to Beyond the Solar System: Student may also learn more about galaxies from the new StarDate Guide to Beyond the Solar System (http://stardate.org/resources/btss/).

The reference section of the black hole database are actual scientific articles. Visit NASA's Astrophysics Data System (astronomy & astrophysics section) to see these articles (http://adsabs.harvard.edu/abstract_service.html). Just enter the author's name and the publication date.

Astronomy websites

Chadra X-ray Observatory: http://chandra.harvard.edu/
Spitzer Space Telescope: http://www.spitzer.caltech.edu/
What Are Astronomers Doing at McDonald Observatory?
http://mcdonaldobservatory.org/research/

Black Hole Database

Object Objects in bold are in the super-massive black hole directory	**Galaxy Type**	**Velocity** km/s Gas, dust, stars orbiting the core	**Bulge Luminosity** Solar Luminosity Units	**Black Hole Mass** Solar Mass Units	**Reference** See NASA's Astrophysics Data System
New Black Hole Candidates					
NGC 314159	S	350	1.00E+04	5.00E+04	Brite et al. 2005
	S	250	1.58E+10	1.00E+09	Faraway et al. 2005
NGC 20051205	S	100	1.00E+04	5.00E+05	Themun et al. 2004
	?	50	1.00E+08	1.00E+09	Stronomer et al. 2005
NGC 271828	E	275	1.00E+07	3.00E+06	Laater et al. 2005
Current Black Hole Candidates					
Milky Way	SBbc	103	1.79E+09	4.00E+06	Ghez et al. 2003
NGC 221 (M32)	E2	75	3.34E+08	2.90E+06	Verolme et al. 2002
NGC 224 (M31)	Sb	160	6.19E+09	7.00E+07	Bender et al. 2003
NGC 598 (M33)	Scd	24	1.89E+06	0.00E+00	Gebhardt et al. 2001
NGC 821	E4	209	2.27E+10	8.50E+07	Gebhardt + 2003
NGC 1023	SB0	205	3.56E+09	4.40E+07	Bower + 2001
NGC 1068 (M77)	Sb	151	5.25E+09	1.50E+07	Greenhill + 1997a
NGC 2778	E2	175	4.25E+09	1.40E+07	Gebhardt + 2003
NGC 2787	SB0	140	1.27E+09	4.10E+07	Sarzi + 2001
NGC 3031 (M81)	Sb	143	2.86E+09	6.80E+07	Bower + 2000
NGC 3115	S0	182	1.89E+10	1.00E+09	Tremaine + 2002
NGC 3245	S0	205	1.13E+10	2.10E+08	Barth + 2001
NGC 3377	E5	145	6.49E+09	1.00E+08	Cretton + 2003
NGC 3379 (M105)	E1	206	1.47E+10	1.00E+08	Gebhardt + 2000a
NGC 3384	S0	143	6.14E+09	1.60E+07	Gebhardt + 2003
NGC 3608	E2	182	1.37E+10	1.90E+08	Gebhardt + 2003
NGC 3998	S0	297	6.79E+07	5.60E+08	Bower
NGC 4258	Sbc	130	1.17E+09	3.90E+07	Miyoshi + 1995
NGC 4261	E2	315	4.25E+10	5.20E+08	Ferrarese + 1996
NGC 4291	E2	242	1.11E+10	3.10E+08	Gebhardt + 2003
NGC 4342	S0	225	1.02E+09	3.10E+08	Cretton + 1999a
NGC 4350	S0	190	1.29E+10	6.00E+08	Pignatelli + 2001
NGC 4374 (M84)	E1	296	5.65E+10	1.00E+09	Bower + 1998
NGC 4395	Sd	30	3.25E+06	3.00E+04	Filippenko
NGC 4459	S0	186	7.11E+09	7.00E+07	Sarzi + 2001
NGC 4473	E5	190	1.41E+10	1.10E+08	Gebhardt + 2003
NGC 4486 (M87)	E0	375	6.37E+10	3.00E+09	Macchetto + 1997
NGC 4486B	E0	185	7.94E+08	6.00E+08	Kormendy + 1997
NGC 4564	E3	162	5.75E+09	5.60E+07	Gebhardt + 2003
NGC 4594	Sa	240	5.40E+10	1.10E+09	Magorrian + 1998

NGC 4596	SB0	152	9.64E+09	7.80E+07	Sarzi + 2001
NGC 4649	E1	385	5.15E+10	2.00E+09	Gebhardt + 2003
NGC 4697	E4	177	1.94E+10	1.70E+08	Gebhardt + 2003
NGC 4945	SB		1.77E+08	1.40E+06	Greenhill + 1997b
NGC 5128 (Cen A)	S0	150	3.25E+10	2.40E+08	Marconi + 2001
NGC 5845	E3	234	4.79E+09	2.40E+08	Gebhardt + 2003
NGC 6251	E2	290	8.24E+10	5.30E+08	Ferrarese + 1999
NGC 7052	E4	266	5.20E+10	3.30E+08	van der Marel + 1998a
NGC 7332	S0		3.70E+09	1.50E+07	Nelson
NGC 7457	S0	67	1.85E+09	3.50E+06	Gebhardt + 2003
Cygnus A	E	270	3.70E+06	2.90E+09	Tadhunter + 2003
IC 1459	E3	340	5.60E+10	2.50E+09	Cappellari + 2002
NGC 7078 (M15)	E1	12	2.00E+06	1500	Gerssen et al. 2003
G1	E1	25	2.00E+07	2.00E+04	Gebhardt et al. 2002

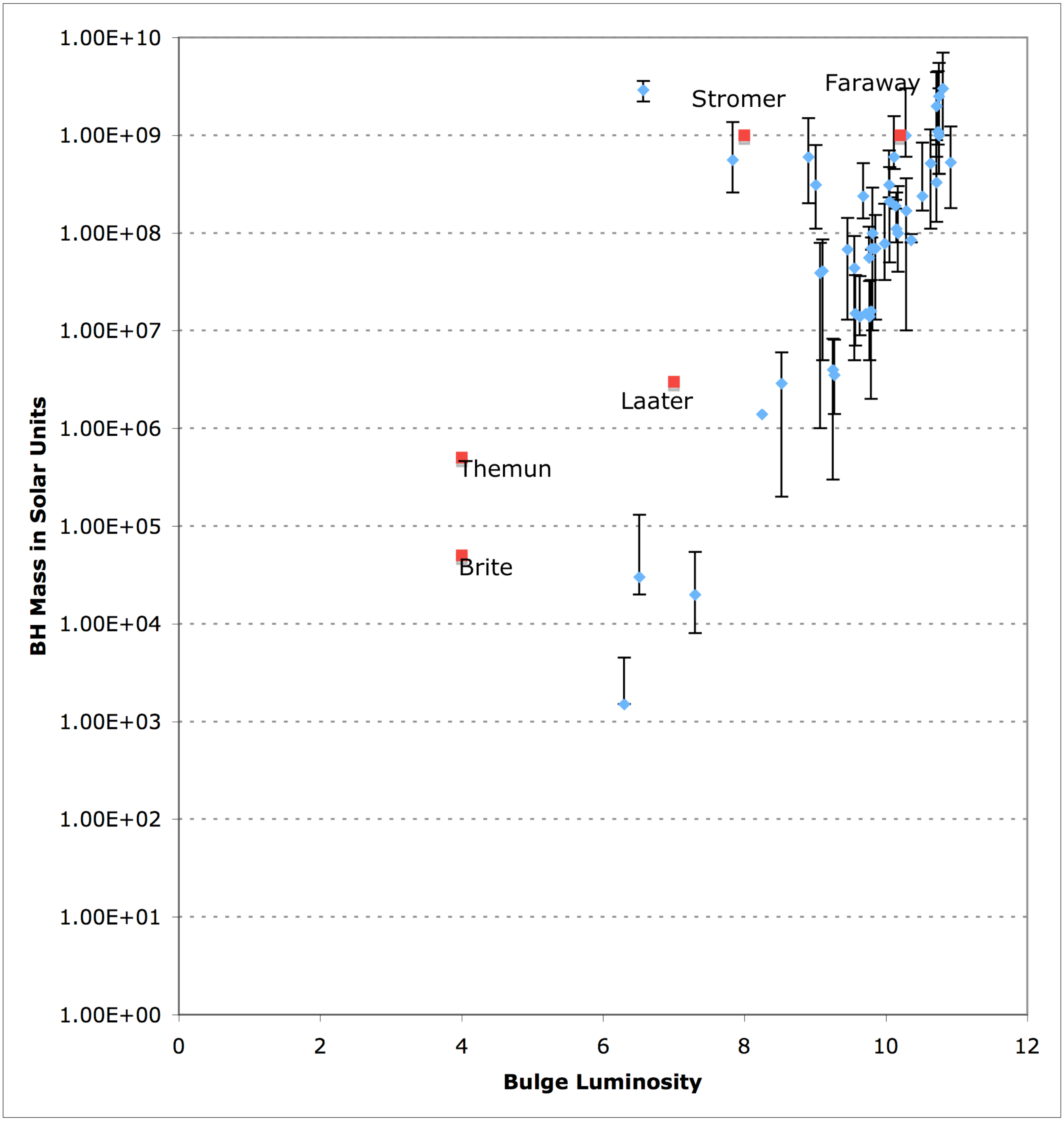
Velocity, Bulge Luminosity, and Black Hole Mass

Velocity: how fast gas, dust, and stars near the core orbit the center of mass of the galaxy. Astronomers can observe a galaxy's core using a telescope and spectrograph. The resulting spectrogram will show both red- and blue-shifted spectral features. Measuring the shift gives astronomers the information they need to calculate the velocity of the materal.

Bulge Luminosity: total amount of power from the galaxy's bulge. Astronomers measure the brightness of the bulge; then with the distance to the galaxy, they calculate its luminosity. The bulge luminosity is expressed in units of the Sun's luminosity (4×10^{26} Watts).

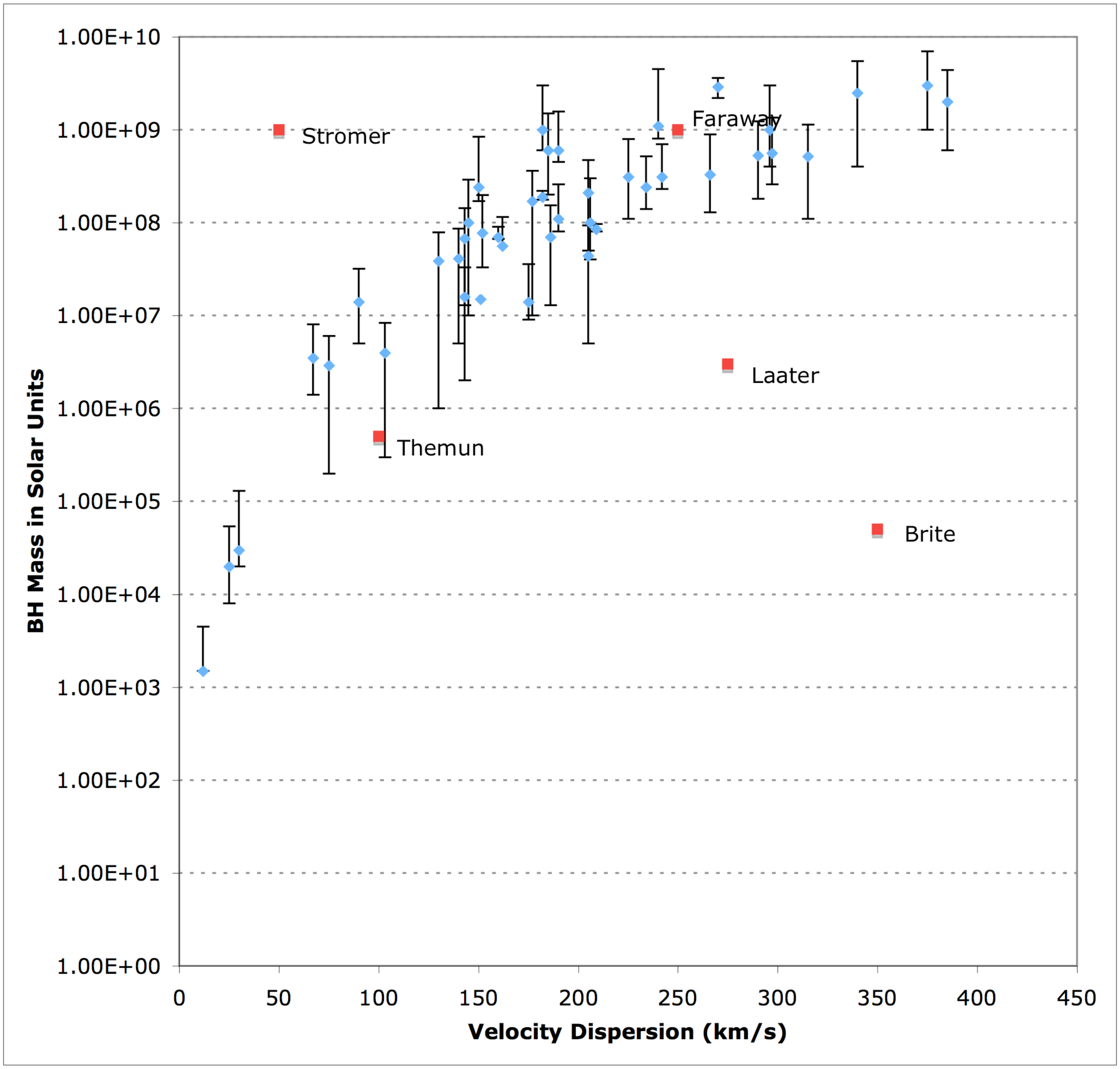
Black Hole Mass: given the velocity and orbits of visible stars and gas orbiting the core, astronomers can calculate the central mass. The mass is expressed in units of the mass of the Sun (2×10^{30} kilograms).

Helpful Plots of Black Hole Data



This is a plot of the calculated super-massive black hole mass verses the luminosity of the galaxy's bulge. The trend in the data shows a strong correlation between the black hole mass and luminosity of the galaxy's bulge (which contains the super-massive black hole). The brackets around the data points represent the uncertainty range of each point; the point represents the most likely value for the black hole mass.

Helpful Plots of Black Hole Data



This will probably be the most helpful to students. It is a plot of all the super-massive black hole masses verses the velocity of gas and dust orbiting near the core. Two of the new candidate entries seem to fall inside the trend. The other three are far outside. The brackets around the data points represent the uncertainty range of each point; the point represents the most likely value for the black hole mass.