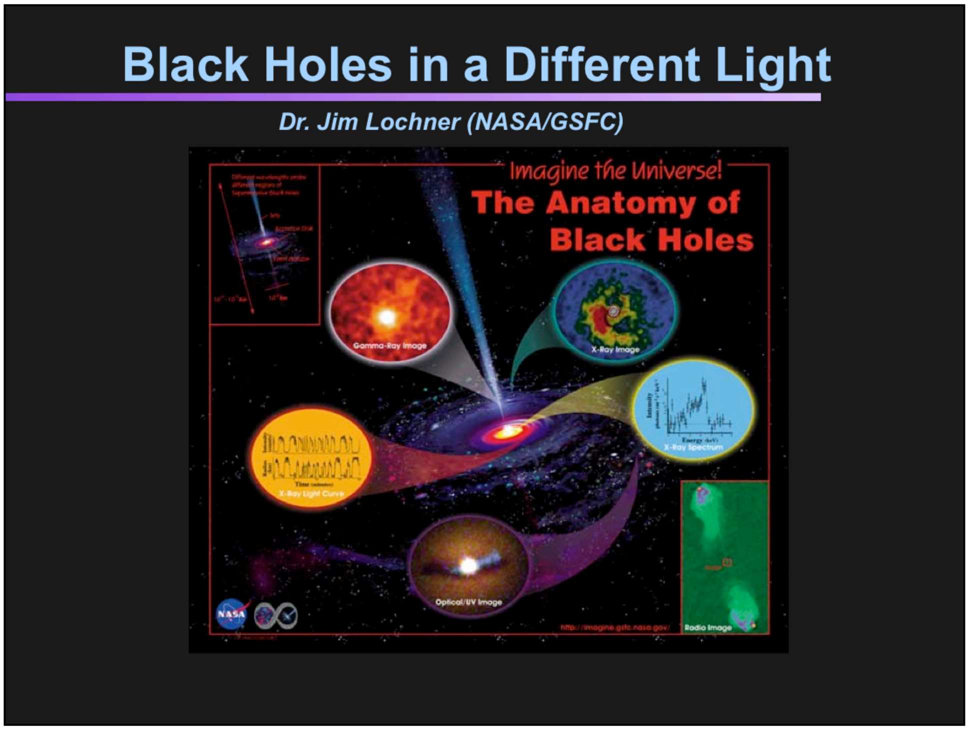


Imagine Anatomy of Black Holes Poster Image

This is the version has been edited from the that was presented at NSTA, March 2002 version.

Updated in Aug 2003 with note for “Groovy X-ray Binary Model” (slide 20) giving the web site address.

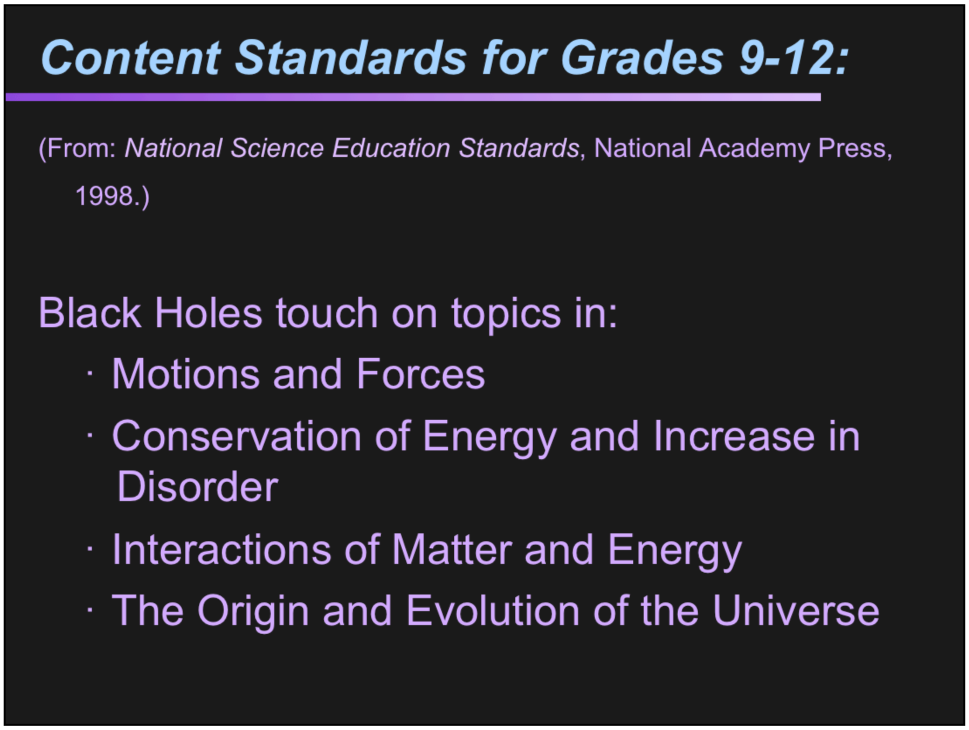
This version was uploaded to Imagine site on 8/28/03

Outline

- Why Teach Black Holes?
- If Black Holes Are Black, How Do We See Them?
  - Getting to Know Your X-ray Binary
- How Do We Know They are Black Holes?
- Are There Any Web Resources Available?

Concepts in Teaching Black Holes

- The escape velocity of light from a star depends upon the star’s mass and radius.
- Gravity is a basic force of nature created between objects that have mass.
- The speed of light, 300,000 km/s, is the universal "speed limit."
- The laws of motion and gravitation are utilized to study the effects of black holes on their immediate environment.


Content Standards for Grades 9-12:
(From: National Science Education Standards, National Academy Press, 1998.)
Black Holes touch on topics in:
· Motions and Forces
· Conservation of Energy and Increase in Disorder
· Interactions of Matter and Energy
· The Origin and Evolution of the Universe

Standards Used in Teaching About Black Holes

(From: *Benchmarks for Science Literacy*, American Association for the Advancement of Science, Oxford University Press, 1993.)

By the end of Grade 12, students should know that:

> Increasingly sophisticated technology is used to learn about the universe. Visual, radio, and x-ray telescopes collect information from across the entire spectrum of electromagnetic waves; computers handle an avalanche of data and increasingly complicated computations to interpret them; space probes send back data and materials from the remote parts of the solar system; and accelerators give subatomic particles energies that simulate conditions in the stars and in the early history of the universe before stars formed.

If Black Holes are Black,
How do We See Them ?

What You Need to Know ...

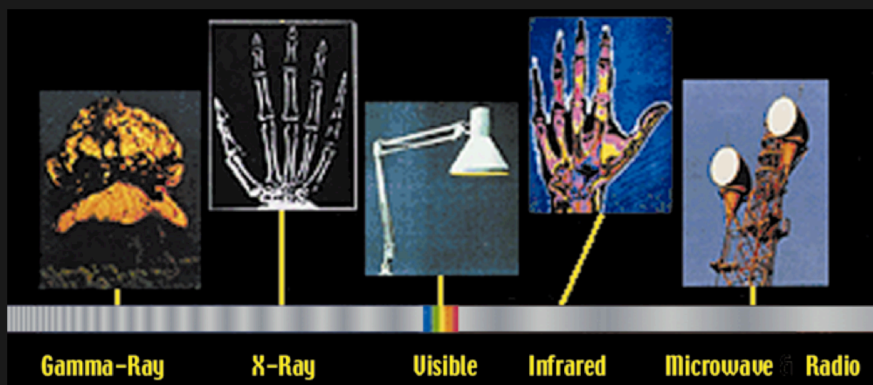
Black Holes Come in Two Sizes:

- "Stellar Mass"
  - 5 - 20 times the mass of the sun
  - Result from supernova explosion of massive star
- Massive ("Active Galaxies")
  - Millions times the mass of the sun
  - Lie in centers of galaxies

Make that Three Sizes (more later …)

EM Spectrum

Electromagnetic Spectrum



Optical

Optical images peer into central regions of other galaxies.

Optical

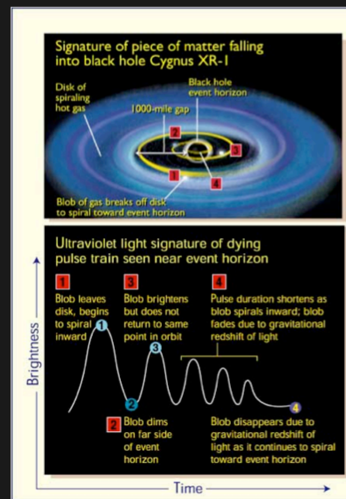
- Material swirls around central black hole.
- Gas near black hole heats up to UV and X-ray temperatures.
- This heats surrounding gas, which glows in the optical.

Image from http://oposite.stsci.edu/pubinfo/PR/2000/37/pr-photos.html
This ring is 260 light-years in diameter.

Ultraviolet

Seeing Matter Disappear

- Hubble observed pulses of UV light emitted by material as it fell into a black hole.
- Pulses arise from material orbiting around intense gravity of the black hole.
- Light pulses, lasting 0.2 s, are red-shifted from X-ray to UV, as they fall into gravity of the black hole.



From http://oposite.stsci.edu/pubinfo/PR/2001/03/

Radio

Radio tells us about motions of particles in magnetic fields.

Using many radio dishes allows us to see small details

A portion of the Very Large Array, Socorro NM

VLA image from http://www.aoc.nrao.edu/intro/vlapix/vlaviews.index.html

Radio Jets from Black Holes

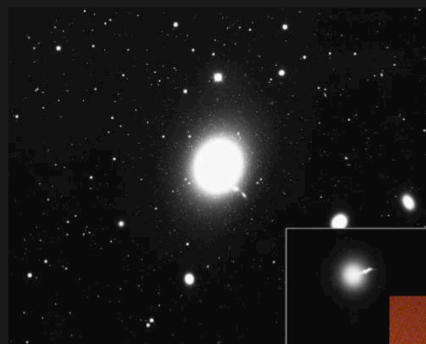
Many black holes emit jets.

- Material in jet moving at 0.9c.
- Jet likely composed of electrons and positrons.

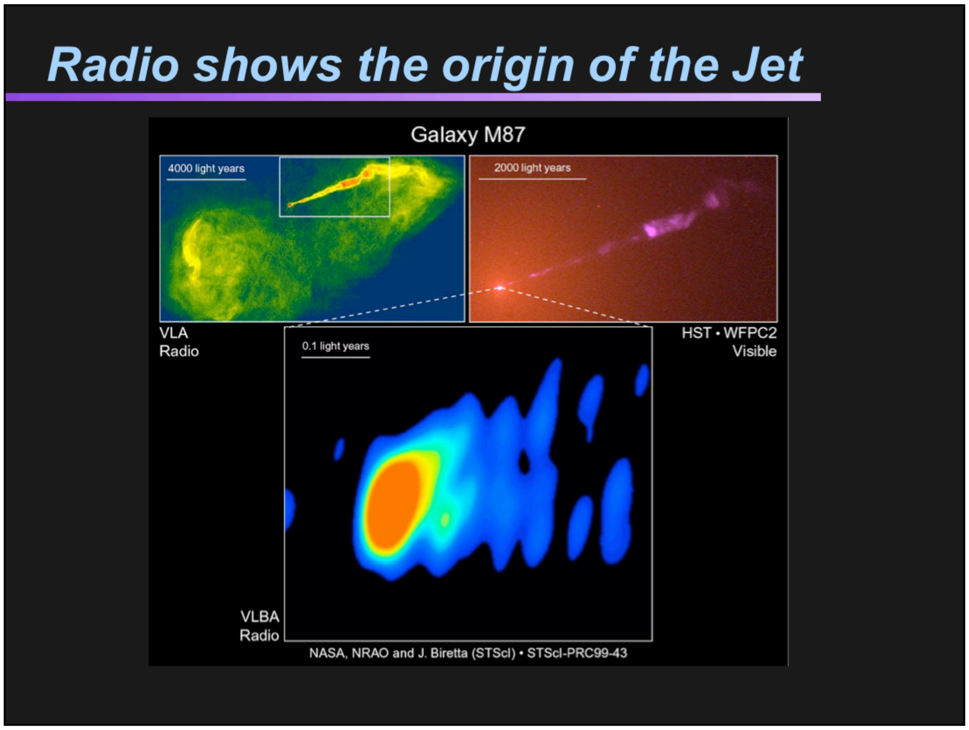
Magnetic fields surrounding black hole expel material and form the jet.

- Interaction of jet material with magnetic field gives rise to Radio emission.

M87 - An Elliptical Galaxy



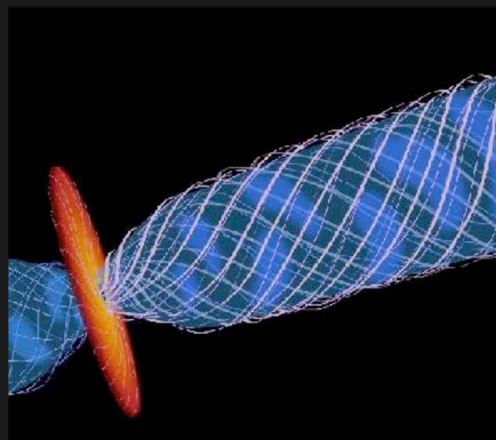
With a curious feature



Optical image from http://www.noao.edu/image_gallery/html/im0090.html

Composite VLA, HST, VLBA from http://oposite.stsci.edu/pubinfo/PR/1999/43/index.html

Our picture of what's happening



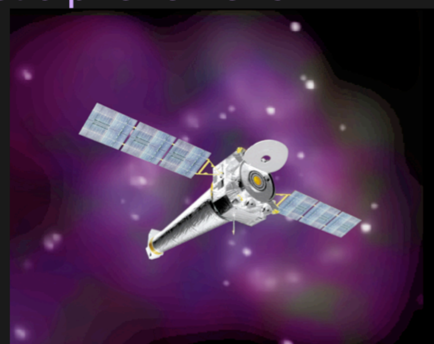
Magnetic field from surrounding disk funnels material into the jet

Illustration from http://www.aoc.nrao.edu/pr/m87.collimation.html

X-ray

X-rays reveal high temperatures and highly energetic phenomena.

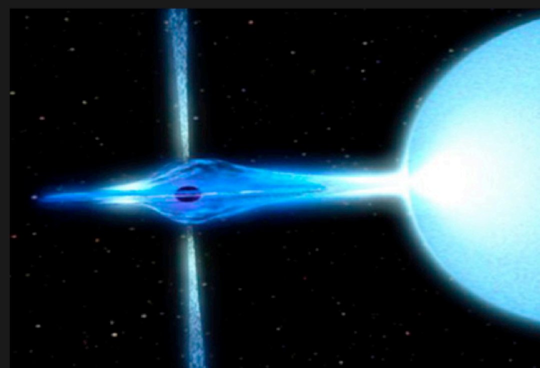
- Current satellites include Chandra X-ray Observatory, XMM, and Rossi X-ray Timing Explorer



Chandra X-ray Observatory

X-rays from Black Holes

In close binary systems, material flows from normal star to black hole. X-rays are emitted from disk of hot gas swirling around the black hole.



In stellar size black hole systems, accretion disks maybe between 6.6 x 10^8 m and 4.2 x 10^10 m in radius. This is ranges from the radius of the sun to 75% of the radius of the orbit of Mercury.

We don't really know the sizes of disks around supermassive black holes in the centers of galaxies. This is primarily because there are no natural size scales in the system to determine the size of the disk, and because we don't know precisely where the material is coming from that feeds the black hole. From the spectra, we infer sizes of 500-1,000 Schwarzschild Radii (~ 3 x 10^14 cm - CHECK ME). If HST images of disks in the centers of AGN represent the outer edges of the disks, then the disks are 22-33 light-years in radius.

Power of Accretion

- Material in Disk gains energy as it falls into black hole.
  - Gravitational energy is converted to kinetic energy.
    - Kinetic Energy is converted to heat and x-rays.
- Up to 42% of the mass of infalling material is converted into energy.
  - That's 10^{38} erg/s ! (100,000x more than sun)

1 Cal = 4.184 J, 1 J = 10^7 erg 10^38 erg = 10^31 J = 2.4 x 10^30 Cal

The "Calories" are kcal, the same as used on food labels.

10^38 erg/s is 100,000 x more than luminosity of the sun.

The instructions for constructing the model are available at

http://heasarc.gsfc.nasa.gov/docs/xte/outreach/HEG/bhm/bhm_intro.html

How Well Do Know your X-ray Binary ?

What force causes material to be pulled toward the black hole ?

Gravity

Why is there a disk surrounding the black hole ?

Gas flows according to rotational motion from orbit of star

What happens to the mass of the black hole as it takes in material from the companion ?

Black hole mass increases

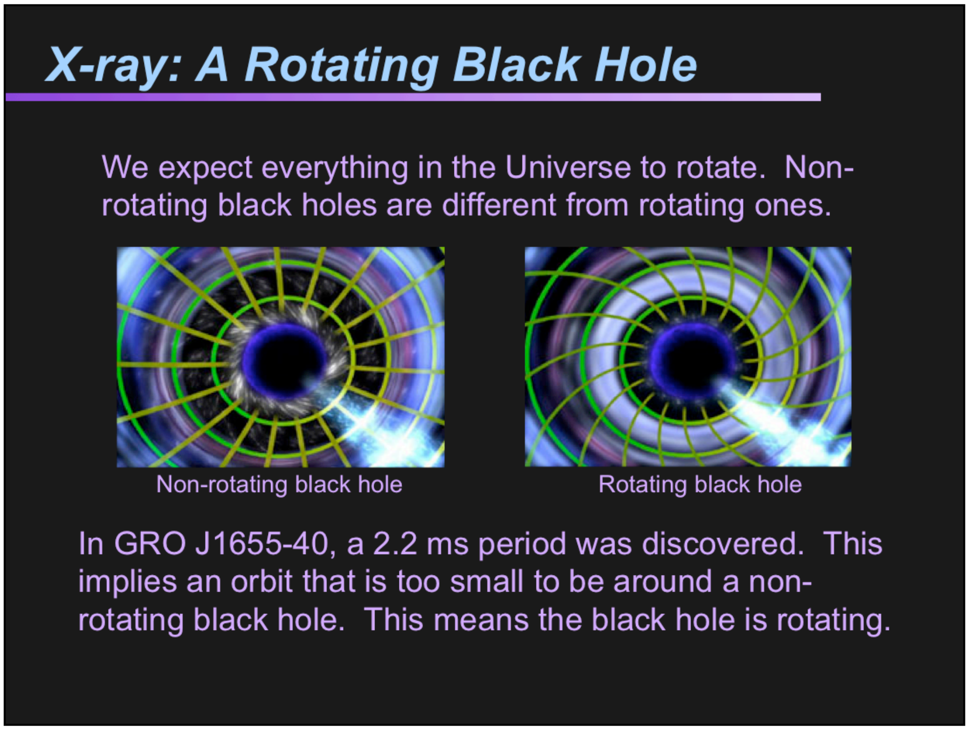
How much material is it ? (alot or a little ?)

A little (compared to mass of Companion Star)

What makes it possible for us to “see” the black hole ?

The disk emits X-rays

This slide is after introducing and discussing the x-ray binary model.



See http://universe.gsfc.nasa.gov/press/cw01_10.html

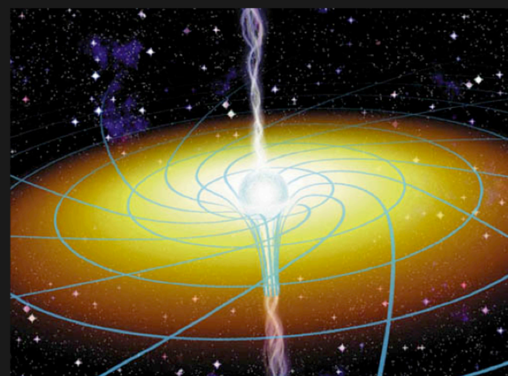
In GRO J1655-40, the 450 Hz (2.2 ms) oscillation implies an innermost stable orbit with max radius of 30 miles (48 km).

If it were not spinning, the innermost stable orbit would have a radius of 40 miles (64 km)

X-ray: Frame Dragging

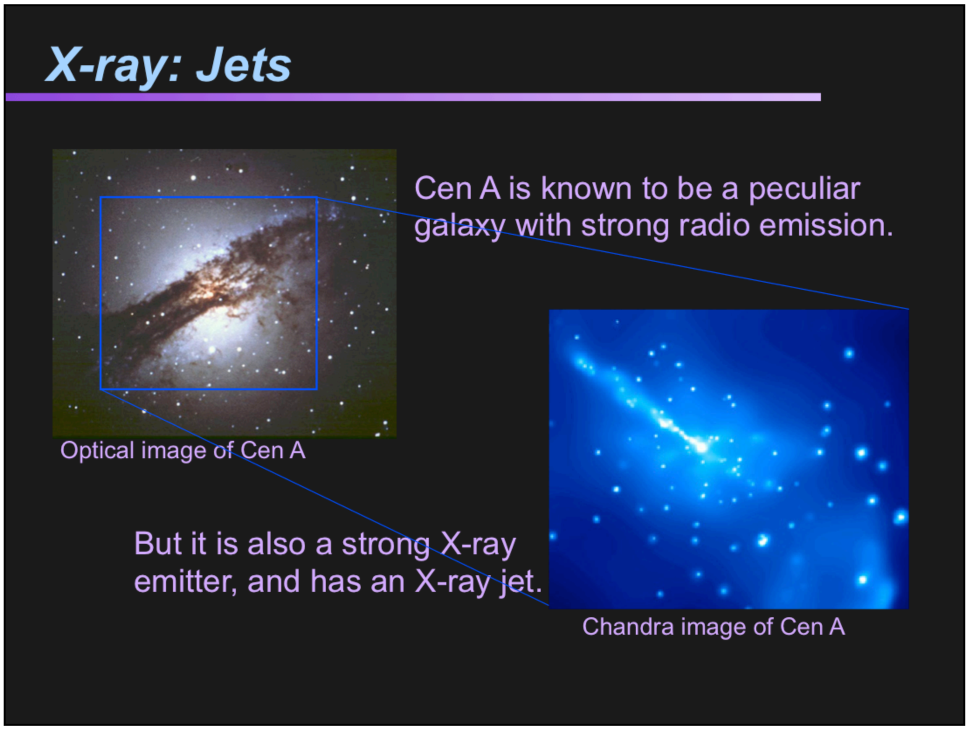
- Detection of a period in GRO J1655-40 due to precession of the disk.

- This precession period matches that expected for frame dragging of space-time around the black hole.



Credit: J. Bergeron, Sky & Telescope Magazine

Precession is motion of the orbit. We can think of this as the motion of spacd-time causing the orbit to rotate. Hence we’ve got precession.

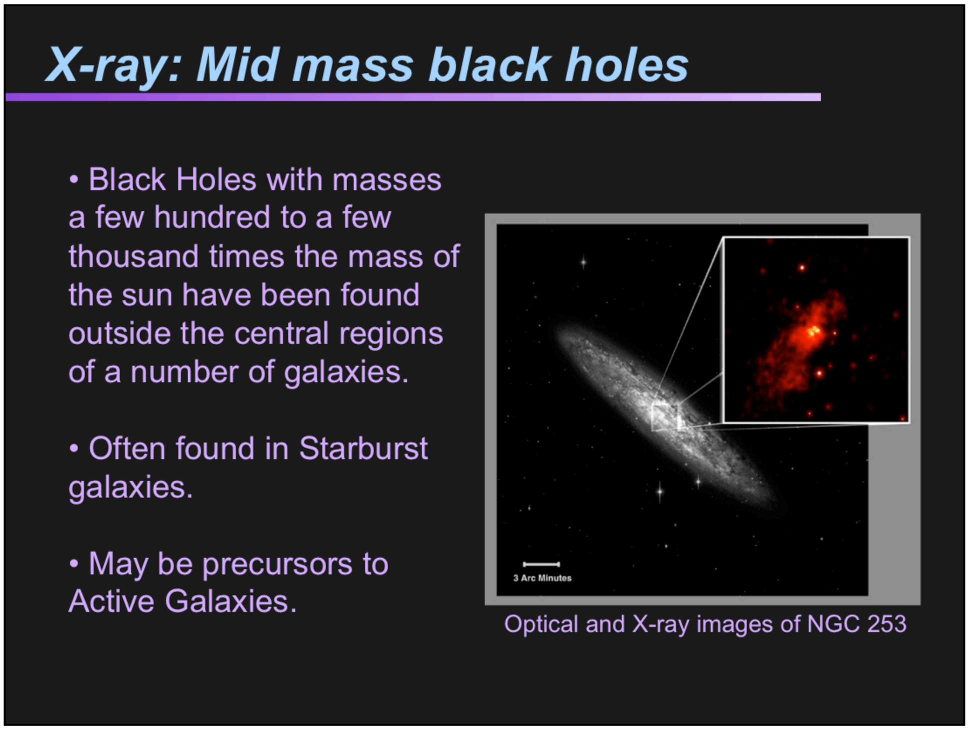


Cen A - http://chandra.harvard.edu/photo/cycle1/0157blue/index.html There's also a good optical image of the galaxy on linked pages. Radio emission is from the jet. The X-ray jet is more uneven than suspected. The point sources are mostly X-ray binaries, with a few supernova remnants as well. Diffuse X-ray glow diffuse produced by several-million-degree gas that fills the galaxy.

Other jets show hot spots at end of jet, where material is running into intergalactic gas. E.g. Pictor A, See http://chandra.harvard.edu/photo/cycle1/pictor/index.html

In 3C373, we see a continuous X-ray emission from the central quasar out to the jet. See http://chandra.harvard.edu/photo/cycle1/0131/index.html

These jets also occur for stellar black holes.



See http://chandra.harvard.edu/press/00_releases/press_091200.html

Illustration from http://universe.gsfc.nasa.gov/press/cw01_12.html, which describes Kim Weavers result that many of these mid-mass black holes are found in starburst galaxies. “Starburst galaxies are known for their brightness caused by a high concentration of young, massive stars and supernova explosions. The bulk of a starburst galaxy's luminosity is from outside of the core region.” “Weaver is finding that starbursts may evolve into AGN. Gas expelled from numerous star explosions may collide and collapse into intermediate-size black holes. These smaller black holes may sink to the center of the galaxy to form a single supermassive black hole. The supermassive black hole, in turn, would grow larger and release fantastic amounts of energy as it pulls in more and more gas from the galaxy core. This would then turn the light source of the galaxy "inside out," making the core bright instead of the disk.” Illustration is of NGC 253, which has 10 such objects, with 3 within 3,000 light years of the center.

Starburst galaxies are undergoing rapid star formation in a short (40-150 million year) time span.

Gamma ray

Gamma Rays reveal the highest energy phenomena

Jets in active galaxies emit gamma-rays as well as radio.

Compton Gamma-Ray Observatory

Gamma ray

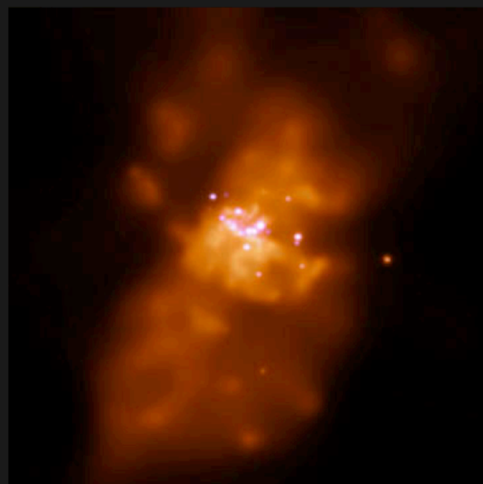
Active Galaxies

- Seyferts - viewing the jet sideways
  - Gamma rays are extension of thermal emission seen in X-ray.
- Blazars - looking down the jet
  - Highly variable gamma-ray luminosity
  - Gamma rays arise from lower energy photons gaining energy from fast moving electrons in the jet.

In gamma rays, we observe two different type of phenomena which we think are coming from the same type of object. We're looking at jets from active galaxies. From different perspectives.

Different views of same phenomena

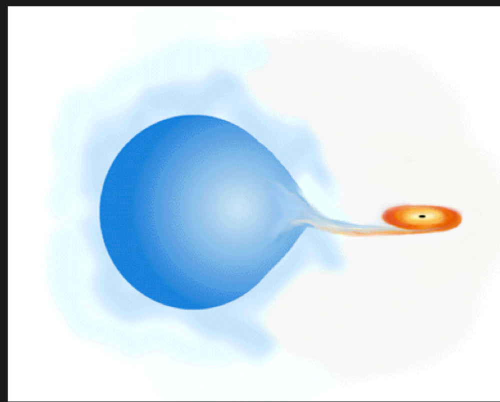
How do we know they are black holes?



Middle mass black holes

Black Holes in Binary Star Systems

- Black holes are often part of a binary star system - two stars revolving around each other.
- What we see from Earth is a visible star orbiting around what appears to be nothing.
- We can infer the mass of the black hole by the way the visible star is orbiting around it.
- The larger the black hole, the greater the gravitational pull, and the greater the effect on the visible star.

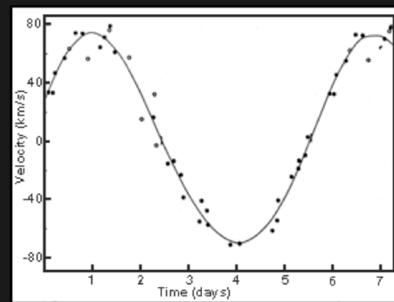


Chandra illustration

Velocities give us Mass

- Gravitational effect of Black Hole on Companion star is measured through the orbital velocity of the Companion.
- What’s the connection ?

$$\frac{(m_{bh})^3 \sin^3 i}{(m_c + m_{bh})^2} = \frac{(v_c)^3 P}{2\pi G}$$

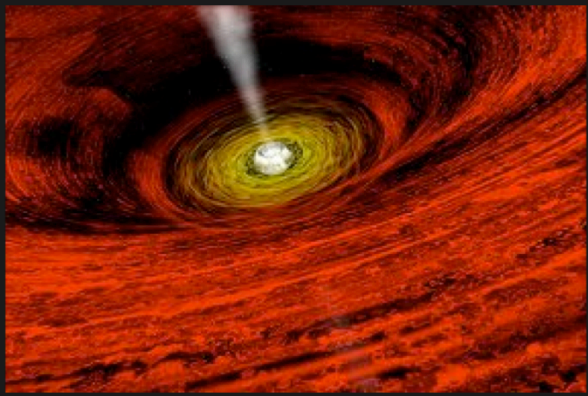


Orbital Velocity of Optical Companion Star in Cygnus X-1

Supermassive Black Holes

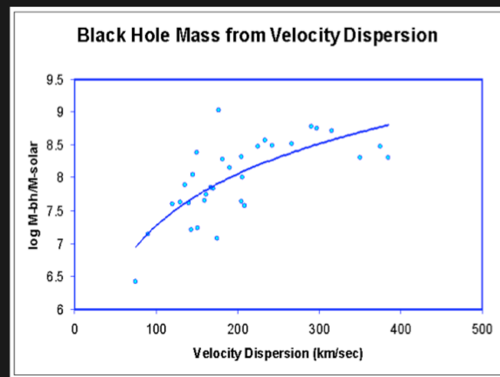
Stars near the center of a galaxy have varied speeds and directions of their orbital motions - that is termed their "*velocity dispersion.*"

The cause of all this chaotic behavior appears to be a super-massive black hole that lurks at the galactic center!



Masses of Supermassive Black Holes

- Hubble Space Telescope can precisely measure the speed of gas and stars around a black hole.
- It discovered a correlation between a black hole's mass and the average speed of the stars in the galaxy's central bulge.
- The faster the stars are moving, the larger the black hole.



The data are taken from a talk given by Karl Gebhardt at the Institute for Theoretical Physics at UCSB in February, 2002. See NSTA version of this talk for the table of values.

The mass of the central SMBH was measured independently, and is given in units of millions of solar masses. The velocity dispersion is given in units of kilometers/second.

Web Resources, page 1

Imagine the Universe – "An Introduction to Black Holes"
http://imagine.gsfc.nasa.gov/docs/science/know_l1/black_holes.html

Amazing Space – " The Truth About Black Holes"
http://amazing-space.stsci.edu/

Hubble Space Telescope Institute
http://hubble.stsci.edu/news_.and._views/cat.cgi.black_holes

Adler Planertarium - "Astronomy Connections - Gravity and Black Holes"
http://www.adlerplanetarium.org/education/ac/gravity/index.html

Gravity Probe B http://einstein.stanford.edu/

Web Resources, page 2

Constellation X-ray Observatory
http://constellation.gsfc.nasa.gov/ga/black_holes.html#what

Imagine the Universe: "You be the Astrophysicist" - Determine the Mass of Cygnus X-1
http://imagine.gsfc.nasa.gov/YBA/cyg-X1-mass/intro.html

Imagine the Universe – "Taking a Black Hole for a Spin"
http://imagine.gsfc.nasa.gov/docs/features/movies/spinning_blackhole.html

Starchild – "Black Holes"
http://starchild.gsfc.nasa.gov/docs/StarChild/universe_level2/black_holes.html

"Virtual Trips to Black Holes and Neutron Stars"

Web Resources, page 3

Universe! – “Voyage to a Black Hole”

http://cfa-www.harvard.edu/seuforum/explore/blackhole/blackhole.htm

Falling Into a Black Hole

http://casa.colorado.edu/~ajsh/schw.shtml

Massive Black Hole Information Center

http://arise.jpl.nasa.gov/arise/infocenter/info-center.html

Everything you need to know about Black Holes

http://www.astro.keele.ac.uk/workx/blackholes/index3.html

Black Holes in a Different Light (this presentation)

http://imagine.gsfc.nasa.gov/docs/teachers/blackholes/blackholes.html