Today in Astronomy 102: prologue in outer space, continued

- Visit 10^9 $M_\odot$, 10^{13} $M_\odot$ and 45 $M_\odot$ black holes

Image: mid infrared picture of Centaurus A, probably the nearest galaxy with a billion-solar-mass central black hole (J. Keene, Spitzer Space Telescope/NASA)

Lecture 03 Astronomy 102 1

A slight deviation … Using orbital motion to probe mass distributions.

Nerds searching for WIMPS in South Dakota. On sale in Lead.

What can we learn from orbital motion?

•

The properties of the orbit (radius, period) depend on the total mass enclosed by the orbit.

- We can measure the mass of the Earth my looking at the motion of the moon around the Earth.
- We can measure the mass of the sun by looking at the motion of the Earth around the sun.
- By looking at the motion of the sun around the center of the galaxy we can determine the mass in our galaxy.

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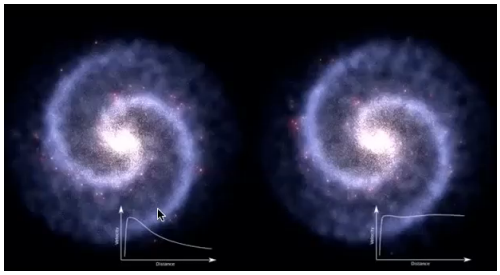
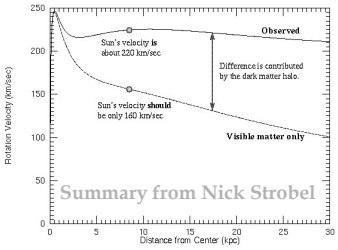
Rotation Curves
Using orbital motion to probe mass distributions.



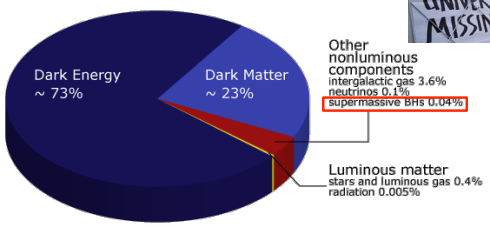
Our sun is moving too fast!
We are moving through a sea of dark matter.



Summary from Nick Strobel

The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two curves is evidence for a **dark matter halo.**

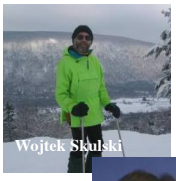
Help!
96% of the universe is missing!



Building the infrastructure to detect dark matter in South Dakota.

LUX: The most sensitive dark-matter detector in the world.

The Rochester team! Key to our success. Three out of five were UR undegraduates.



Dev
Ashish
Khaitan

No WIMPs have been seen yet in South Dakota.

Inside the Large Underground Xenon dark matter detector. Matthew Kapust/South Dakota Science and Technology Authority

END OF DEVIATION. BACK TO BLACK HOLES.

Journey to Gargantua and 3C 273

Gargantua is a *hypothetical* black hole near the quasar 3C 273, 2×10^9 light years from Earth.

Travel in starship: acceleration = Earth's gravity ("1*g*"), speed close to the speed of light most of the time.

The trip takes 42 years, measured on the starship, but **2 billion years**, measured by an observer on Earth. (Extreme relativistic length contraction!)

Properties of Gargantua:

- Mass = $1.5 \times 10^{13}\ M_\odot$
- Horizon circumference = 29 ly
- Rotation period = infinite (it's not spinning)
- Not very much interstellar gas falls into hole.

Properties of 3C 273

... a real galaxy, with a large black hole at its center. 3C 273 was the first **quasar** identified by astronomers.

- Black hole mass = $2 \times 10^9 M_\odot$
- Horizon circumference = 0.3 ly
- Rotation period = Fast! (We can't tell quite how fast.)

A spinning **accretion disk** of gas surrounds the black hole; much of this material will eventually be swallowed. Energy released in this infall currently gives the black-hole region an enormous luminosity, about $10^{12} L_\odot$.

Accretion = growth by addition of material.

A side effect of the infall: ejection of two **beams** or **jets** of matter, perpendicular to the disk, at speeds close to the speed of light. (Recall the image of GRO J1655-40, seen last time…)

Rank these objects in order of mass, small-large:

1. The Sun
2. Gargantua
3. The Milky Way Galaxy
4. A typical galaxy cluster
5. 3C 273's black hole

A. 5-2-1-3-4 B. 1-5-2-3-4 C. 1-3-4-5-2 D. 1-5-3-2-4

(Artist's) view of 3C 273 from Gargantua

Ejected material: "twin jets," speeds near the speed of light

Accretion disk

Black hole (at center of disk)

Foreground material (near Gargantua)

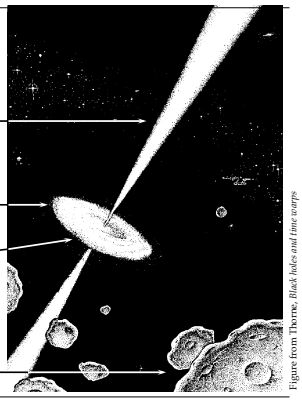
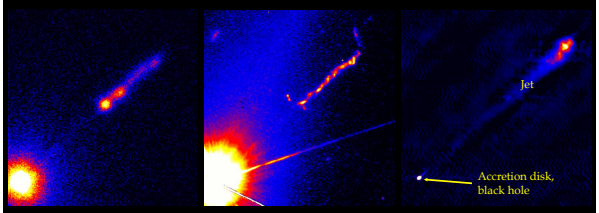


Figure from Thorne, *Black holes and time warps*

Astronomer's view of 3C 273, from Earth or thereabouts



X ray image, by the NASA *Chandra* X-ray observatory (CXO).

Visible-light image, by the NASA *Hubble* Space Telescope (HST).

Radio image, by the Multi-Element Radio Linked INterferometer (MERLIN).

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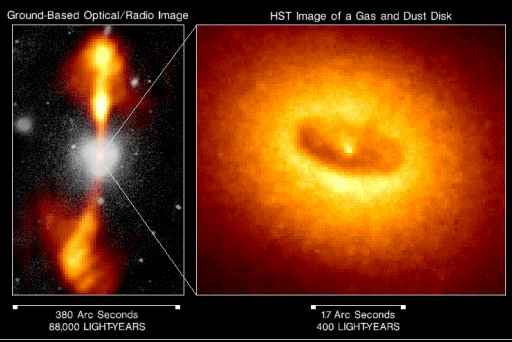
Astronomer's view of radio galaxy NGC 4261



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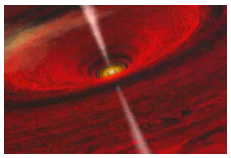
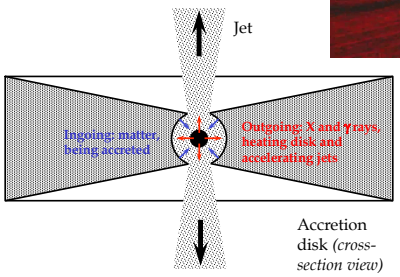
Structure of an accretion disk



(Chandra X-ray Center, NASA/CfA)



Accretion disk *(cross-section view)*

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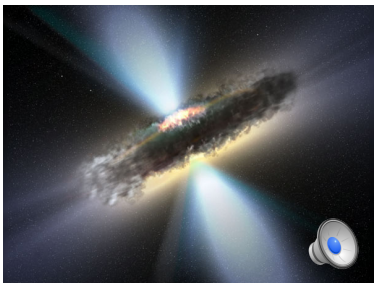
Mid-lecture break (3 minutes 34 seconds)

Homework #1 is due Monday, February 1, at 8.30 am.

The correct answers can be viewed, beginning 24 hours later.



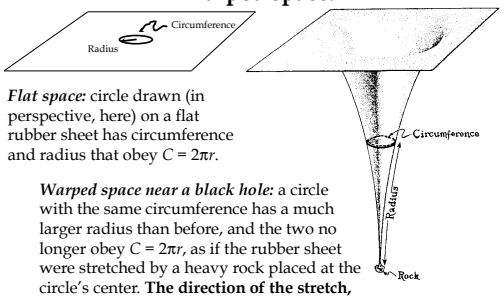
Artist's conception of a quasar: an accreting black hole surrounded by a dusty disk (V. Beckmann, NASA and ESA).

Exploring the neighborhood of Gargantua

Descend (fall, then brake with the rockets) to a location just above the horizon, such that your orbit would have a circumference 1.0001 times the horizon's, where the gravity is 10*g*, if you could orbit there.

- ❑ It takes 13 years to descend at light speed from a stable orbit (a few horizon circumferences) to that point.
  - An extreme example of the **warping of space** near a black hole!
- ❑ The appearance of the sky changes dramatically as you descend.
  - Instead of being spread out in all directions, the stars and galaxies are compressed into an ever-shrinking circle directly overhead.
  - The colors of stars and galaxies become bluer .

Recall from last time: the "rubber sheet" analogy of warped space.



Flat space: circle drawn (in perspective, here) on a flat rubber sheet has circumference and radius that obey $C = 2\pi r$.

Warped space near a black hole: a circle with the same circumference has a much larger radius than before, and the two no longer obey $C = 2\pi r$, as if the rubber sheet were stretched by a heavy rock placed at the circle's center. **The direction of the stretch, though, is not in physical space, but in hyperspace.**

(figure from Thorne, *Black holes and time warps*)

Space warping near Gargantua

Thus we measure the distance between circles of 3 horizon circumferences (87 ly) and 1.0001 horizon circumferences (29 ly) to be 13 ly. What would the distance appear to be, to a distant observer?

A. 87 ly – 29 ly = 58 ly, longer than we measure.
B. (87 ly – 29 ly)/2π = 9.2 ly, shorter than we measure.
C. 13 ly, the same as we measure.
D. Zero ly, because it's so far away.

Near the horizon, Gargantua's gravity bends the paths that light can follow, "compressing" the sky

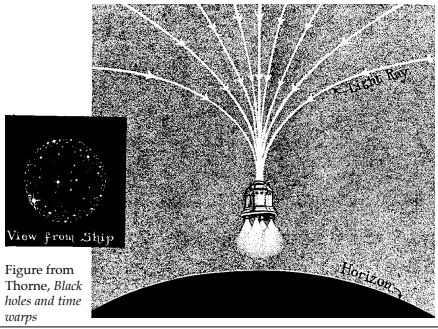


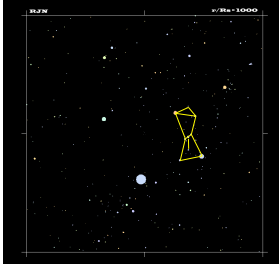
Figure from Thorne, *Black holes and time warps*

Light rays

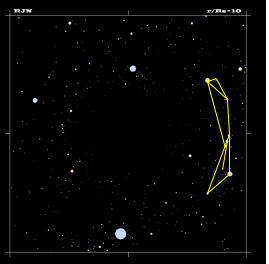
Your ship

Horizon

View of the sky, approaching a black hole



A long way away. Note the positions of the more distant stars.



Closer to the black hole. Note how the stars appear shifted. (Courtesy Robert Nemiroff, MTU.)

What are you looking at?

What do you think the blackness actually is? At what are your eyes pointed when you look in those directions?

A. The horizon B. The volume within the horizon
C. The point-like mass at the center D. Nothing

Journey home

You return to a hypothetical pair of black holes in what used to be the Orion Nebula, 1500 light years away from Earth.

- Travel in starship: acceleration = Earth's gravity ("1 g"), speed close to the speed of light most of the time.
- As before, the trip from Gargantua takes 42 years, measured on the starship, but 2 billion years, measured by an observer on Earth.
- You arrive just in time to watch the black holes coalesce into one single, spinning black hole.
- Just afterwards, your spaceship is rocked violently by the burst of **gravity waves** (gravitational radiation) released in the course of the coalescence.

Rank in order of time span, short to long

1. Life span of a $100 M_{\odot}$ star. 2. Life span of the Sun.
3. Current age of the Sun. 4. Current age of the Universe.
5. The trip we just (hypothetically) took.

A. 1-2-3-4-5 B. 5-3-2-1-4 C. 1-5-3-2-4 D. 5-4-3-2-1

Gravity waves: relativistic, gravitational relatives of light

Light consists of oscillating **electric and magnetic fields**.

- As light encounters matter, these fields push around the **electric charges** (a.k.a. **ions**) therein.
- Electric charge comes in two varieties we call "positive" and "negative," that move in opposite directions in a given electric or magnetic field.
- Matter is made up of equal numbers of positive and negative charges, bound together, so light doesn't move it around much.

Gravity waves consists of an oscillating **gravitational field**.

- As they encounter matter, the field pushes around the **masses** therein.
- Only one variety of mass exists! The wave moves, squeezes and stretches all the matter it encounters.

Properties of your new black hole

- Mass = 45 $M_\odot$
- Horizon circumference = 533 km.
- Rotation period = 0.0037 seconds
- 20% of the hole's total energy lies in the **swirl of space** just outside the horizon, on the equator: 10^4 times as much energy as the Sun radiates in its entire lifetime.

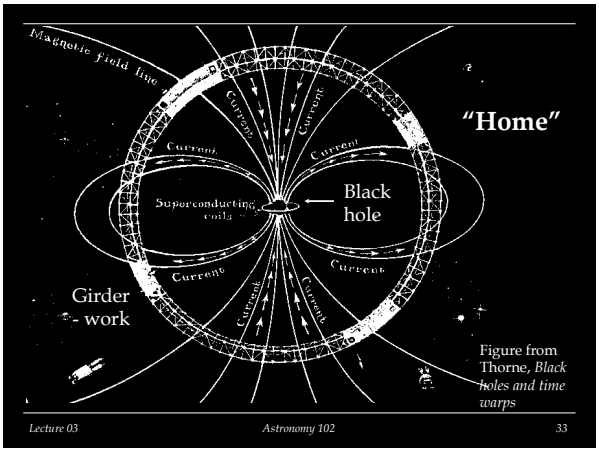
Your crew builds a giant girder-work, 5×10^6 km in circumference (2.2 times that of the Moon's orbit around the Earth), rotating once every half hour to provide 1*g* gravity on its inner and outer surfaces.

The energy of the "swirl" is tapped to fuel the new city on the girder-work.

The "swirl of space" near the horizon

The extreme warping of space near a horizon is an indication that **space itself is stuck to the horizon**, in the view of a distant observer.

- Like time stopping at the horizon, in the view of a distant observer. (Remember Arnold's fall…)
- Thus, if the horizon moves, it drags space along with it. A rotating horizon winds space round and round the horizon: this is the "swirl of space."
- Upshot: any part of any object placed in the "swirl" will be dragged around with it. Connect that "crank" to a machine and the rotating black hole will turn the crank, usually for a very long time.



Summary: weird properties of black holes and relativity, that we need to explain

Lengths appear to contract when travelling at near-light speeds.

No speed can exceed light's.

Nothing can escape from within a black hole's horizon.

High-energy light is given off by ions falling into a black hole.

The "swirl of space" around a rotating black hole.

Gravity waves.

Near a black-hole horizon:

- Space warps (e.g. orbit radius much larger than $C/2\pi$)
- Time warps (to a distant observer time seems to slow down and stop near a horizon)
- Gravitational redshift (same as time warp)
- Very strong gravity and tidal forces
- Gravity and tidal forces very near horizon are *less* for a heavier black hole than for a lighter one
- Orbits smaller than 3 horizon circumferences: "reverse thrust" required to change, resulting in instability
- No orbits smaller than 1.5 horizon circumferences
- Sky compressed into a small circle overhead

The End

Extrasolar Super-Earth Gliese 1214b Might Hold Water

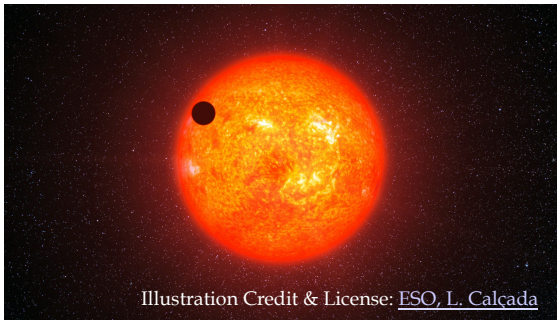


Illustration Credit & License: ESO, L. Calçada