PROLOGUE IN OUTER SPACE

PROBLEM SET #1 ON WEBWORK – DUE TOMORROW (WEDNESDAY) AT MIDNIGHT

PROLOGUE IN OUTER SPACE

Visit $10^6 M_\odot$, $10^{13} M_\odot$, 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)

JOURNEY TO SAGITTARIUS A*

Sagittarius A* is another black hole, a good deal less hypothetical than Hades, that lives at the exact center of our Milky Way galaxy, about 26,000 light years away from Earth.

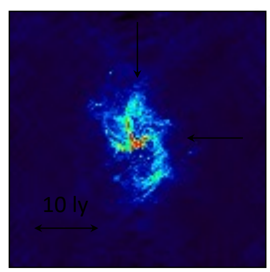
- Travel in starship: acceleration = Earth's gravity again, speed close to the speed of light for most of the time
- This time, the trip takes **20 years,** measured on the starship, but **25,600 years** as measured by an observer on Earth.

Properties of Sagittarius A*:

- Mass $= 10^6 M_\odot$ (it has been measured to be $4.297\times10^6 M_\odot$)
- Horizon circumference $= 3.99\times10^7$ km (a factor of 17 larger than the Moon's orbit)
- Rotation period = close to infinite (rotating very slowly, if at all)
- Again, not very much interstellar gas falls into the black hole.

THE NEIGHBORHOOD OF SAGITTARIUS A*

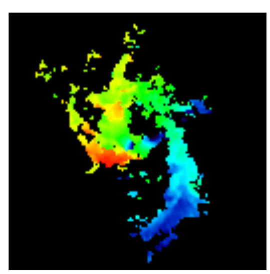
The immediate neighborhood of the black hole appears in this false-color radio-wave image as a small white dot (follow the arrows). The "swirls" are streamers of ionized gas orbiting the black hole and the star cluster that surrounds it.



Data: D. Roberts & M. Goss (1993), using the NRAO Very Large Array radio telescope

This image is a color code of the speed of the ionized gas along our line of sight.

- Red = receding at about 200 km/s
- Blue = approaching at about 200 km/s

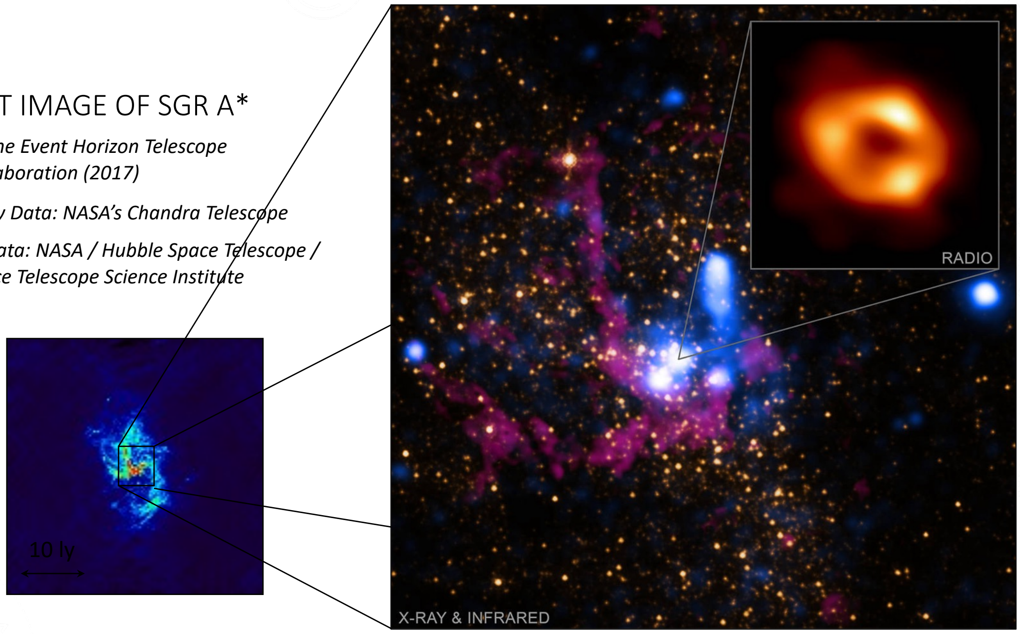


EHT IMAGE OF SGR A*

By the Event Horizon Telescope Collaboration (2017)

X-ray Data: NASA's Chandra Telescope

IR Data: NASA / Hubble Space Telescope / Space Telescope Science Institute

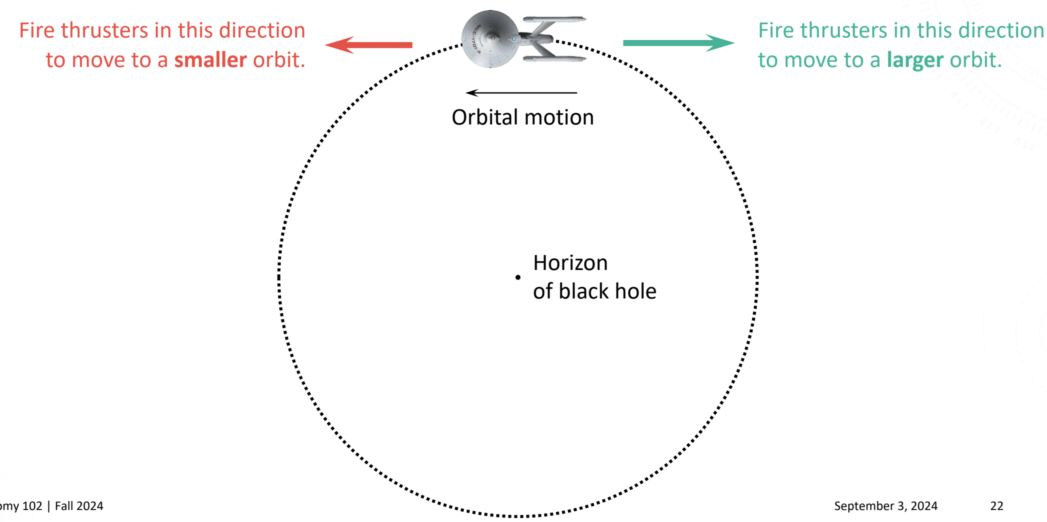


CHANGING ORBITS AROUND SGR A* (FOR ORBITS CLOSE TO THE HORIZON SIZE)

As the starship approaches the horizon, we would notice ourselves doing different things than before to satisfy the conservation of energy and spin when changing orbits.

- For orbits 3 times the horizon circumference and smaller, the thrust must be applied **backwards** to have the desired effect on orbital changes: speed up to reduce orbital spin, put on the brakes to increase spin.
- This is yet another result of the **warping of space** near the horizon by the black hole's strong gravity.
- As a result, orbits smaller than 3 horizons are unstable. An orbiter without thrusters which gets a kick in the forward (reverse) direction will spiral into the black hole (careen away from the black hole).

CHANGING ORBITS AROUND SGR A* (FOR ORBITS MUCH LARGER THAN THE HORIZON)



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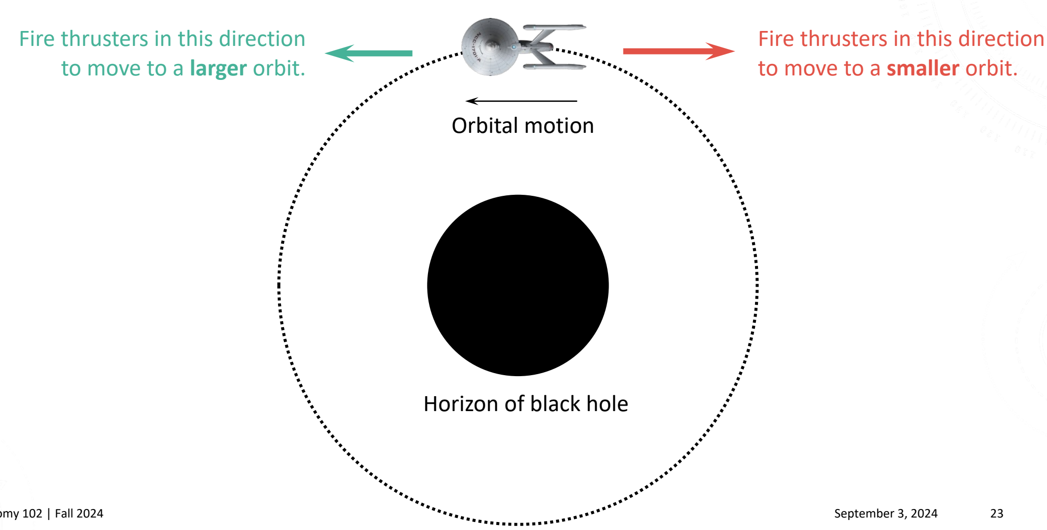
CHANGING ORBITS AROUND SGR A* (FOR ORBITS CLOSE TO THE HORIZON SIZE)



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EXPLORING THE NEIGHBORHOOD OF SGR A*

Take a capsule into orbits progressively smaller in circumference, trying to reach an orbit 1.0001 times larger than the horizon (again).

- Tidal forces are bearable in orbits as small as 1.5 times the horizon circumference.
- There are **no orbits** smaller than 1.5 horizon circumferences, where the orbital speed is the speed of light.
- To get closer, one must attempt a "vertical landing:" balancing the black hole's gravitational pull with thrust instead of centrifugal force.
- Calculations: hovering at 1.0001 horizon circumferences takes a thrust of $150g$! Better find a *more* massive black hole.

JOURNEY TO GARGANTUA AND 3C 273

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

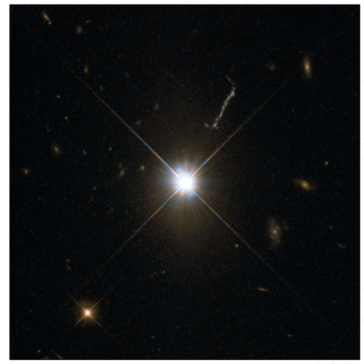
Travel in starship: acceleration = Earth's gravity ("$1g$"), speed close to the speed of light for most of the journey.

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

Properties of Gargantua:

- Mass $= 1.5\times10^{13} M_\odot$
- Horizon circumference = 29 ly
- Rotation period = infinite (it is not spinning)
- Not very much interstellar gas falls into the black 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.

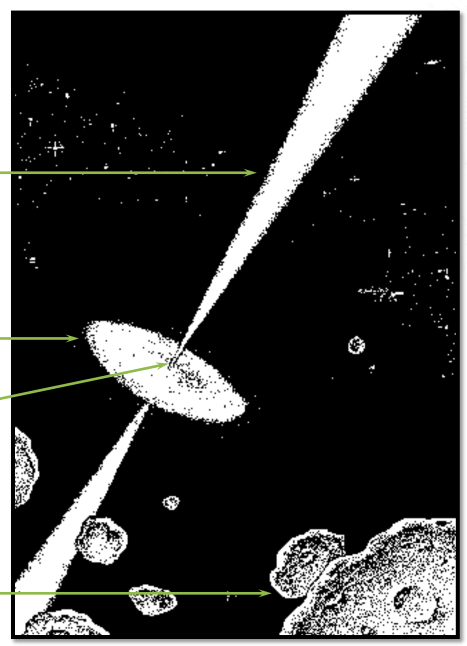
- Black hole mass $= 8.86 \times 10^8 M_\odot$
- Horizon circumference = 55 AU
- Rotation period = fast! (We cannot tell quite how fast.)

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 $10^{12} L_\odot$.

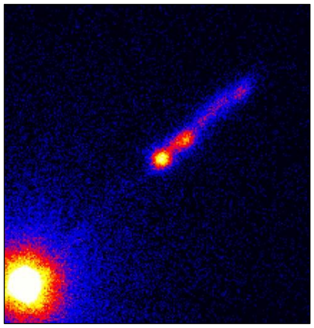
Accretion = growth by addition of material

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…)

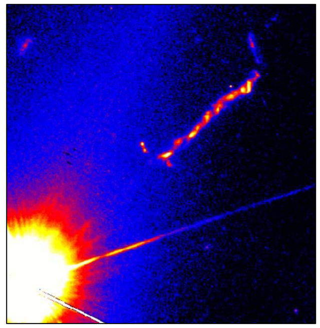
(ARTIST'S) VIEW OF 3C 273 FROM GARGANTUA



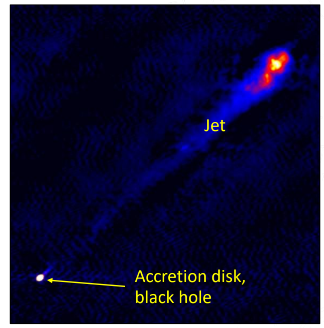
ASTRONOMER’S VIEW OF 3C 273 (FROM EARTH)



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

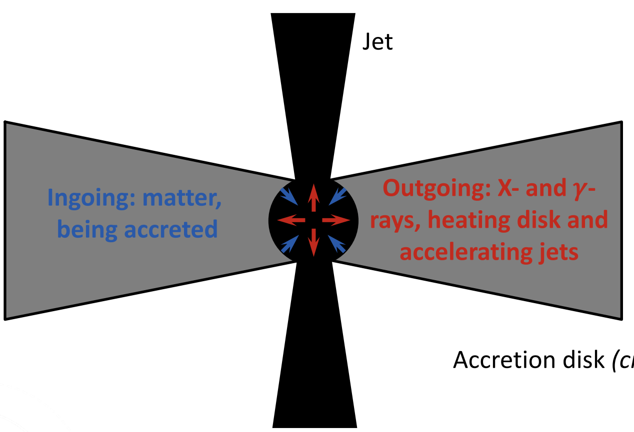


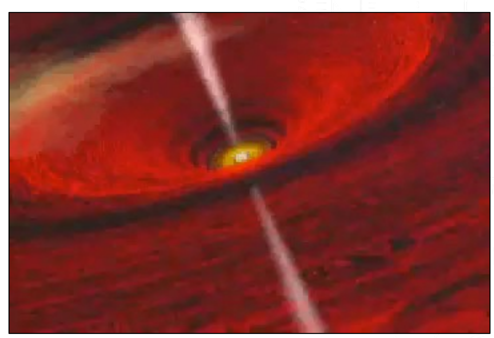
Visible-light image, by the NASA *Hubble* Space Telescope (HST)



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

STRUCTURE OF AN ACCRETION DISK





Accretion disk *(cross-section view)*

WHICH IS LARGER?

Rank these objects in order of mass, from smallest to largest.

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

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. The gravity here is $10g$, if you could remain in orbit.

- 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!

SPACE WARPING NEAR GARGANTUA

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

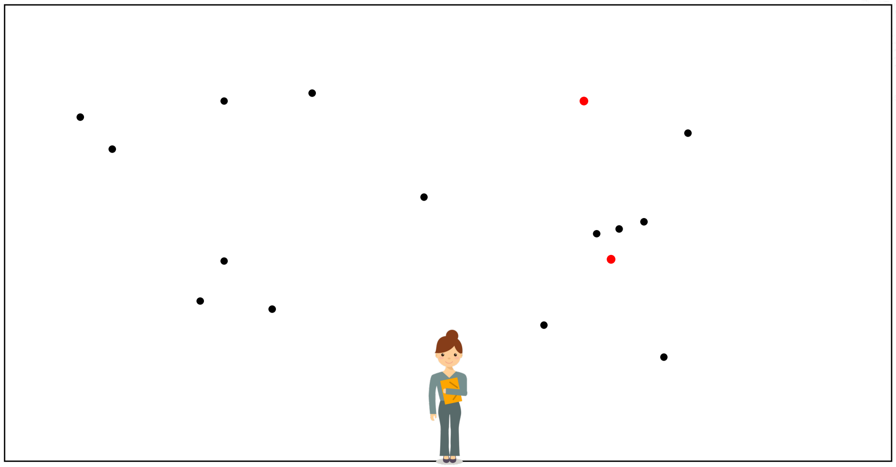
D. 0 ly, because it is so far away

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. The gravity here is 10*g*, if you could remain in orbit.

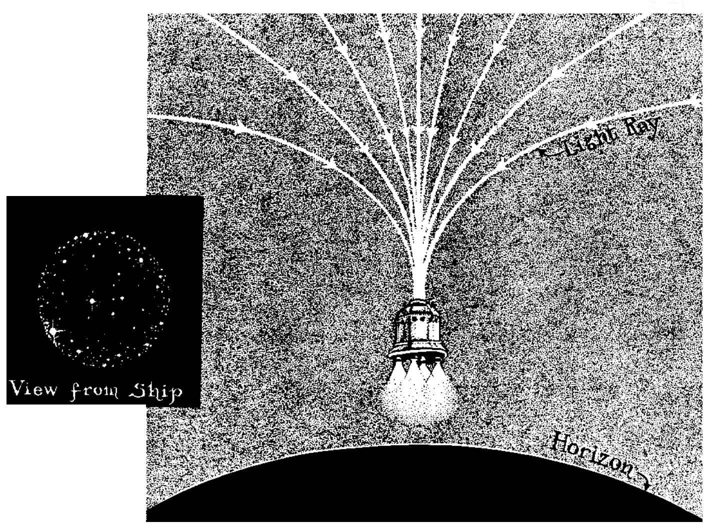
- It takes 13 years to descend at light speed from a stable orbit (a few horizon circumferences) to that point. An extreme example of the **warping of space** near a black hole!
- The appearance of the sky changes dramatically as you descend.
  - Instead of being spread out in all directions, the stars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

VIEW OF THE SKY FROM JUST ABOVE A PLANET'S SURFACE

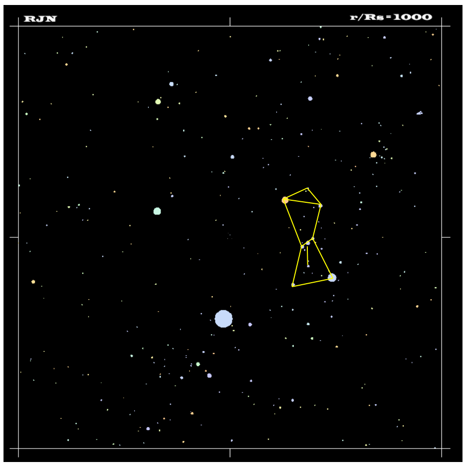


VIEW OF THE SKY NEAR GARGANTUA'S HORIZON

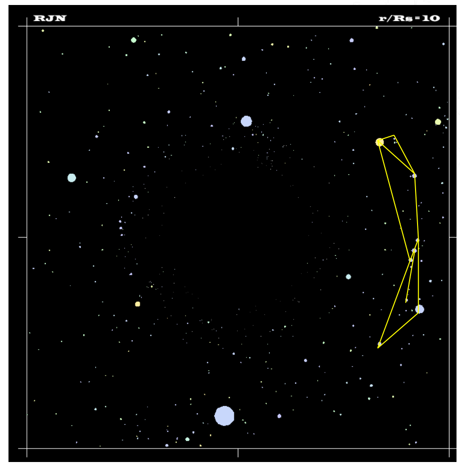
Near the horizon, Gargantua's gravity bends the paths that light can follow, "compressing" the sky.



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 of Robert Nemiroff, MTU)*

VIEW OF THE SKY FROM JUST ABOVE A BLACK HOLE'S HORIZON

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 ("$1g$"), speed close to the speed of light for most of the time
- As before, the trip from Gargantua takes 42 years, measured on the starship, but 2 billion years as 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 violently rocked by the burst of **gravitational waves** (gravitational radiation) released during the coalescence.

WHICH LASTS THE LONGEST?

Rank the following timespans from shortest to longest.

1. Life span of a $100M_{\odot}$ 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

GRAVITATIONAL 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 does not move it around much.

Gravitational waves consist of an oscillating **gravitational field**.

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

DETECTING GRAVITATIONAL WAVES

The easiest way to detect gravitational waves is by observing them push and pull the mass around us.

LIGO (Laser Interferometer Gravitational-Wave Observatory) is a massive interferometer that is about 4000 m long.

- Interferometers use light to detect differences in the path length.
- Light is a wave – if you add two waves that are in phase, they will **constructively** interfere; if they are out of phase, they will **destructively** interfere.
- LIGO is sensitive enough to detect a path difference of < 0.0001 of the diameter of a proton.