Today in Astronomy 102

- ❑ Prologue in outer space: hypothetical journey to two representative black holes.

The "Coalsack," a dark nebula in the Southern Cross, is quite black but unrelated to black holes.

Photograph by David Malin, Anglo-Australian Observatory.

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Prologue in outer space: what black holes are like

A black hole is a highly-gravitating object from which nothing, not even light, can escape once it has fallen in.

As is done in Thorne's book, we now consider a hypothetical trip to some representative, celestial black holes with a wide range of mass.

Many strange effects will be encountered along the way. **We will explain all of these effects eventually this semester**, but for now we just want you to see an overview of the effects, and what life is like in the neighborhood of black holes.

Image: part of the Hubble Ultra Deep Field (NASA/Space Telescope Science Institute)

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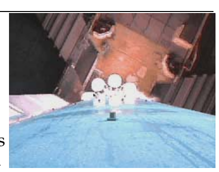
Journey to Hades



Launch of the Spitzer Space Telescope.

Hades is a hypothetical black hole near the bright star Vega (in the constellation Lyra), 26 light years from Earth.

- ❑ Travel in starship: acceleration = Earth's gravity ("1 g"), speed close to the speed of light most of the time. **Nothing travelling through physical space can go faster than the speed of light.**
- ❑ The trip takes 6 years, measured on the starship, but 26 years, measured by an observer on Earth.
- ❑ This difference is a prediction of Einstein's theory of relativity: **length contraction**. The distance to Hades looks shorter from the moving starship than from the stationary Earth (or Hades). (We will discuss this in detail in just a few lectures.)
- ❑ Enter orbit above Hades: orbit circumference = 10^6 km (half that of the Moon's orbit), revolution period = 5 minutes, 46 seconds (speed in orbit = 2890 km/s).

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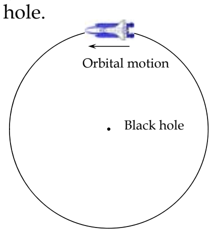
A note about orbits

Orbiting a black hole is just like orbiting a planet or a star, if the orbit is much larger than the black hole.

- No thrust is required to **stay** in an orbit.
- In orbit, the force of gravity is balanced by the **centrifugal force** of the orbiter's motion, which depends upon the speed in orbit.
- If the starship has the *wrong* speed for the orbit, it will drift into a different orbit which is a match for the speed. This is called orbital **stability.**



The black hole itself

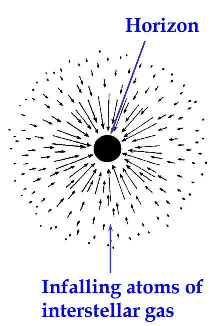
Black hole and swirl of infalling gas, seen from a range of angles (Phil Armitage and Chris Reynolds, U. Colorado).

The special feature of black holes is that there is a distance closer than which nothing can get away.

- That special distance traces out a surface that we call the **event horizon** or simply the **horizon.**
- The horizon is just a set of points in space; there's no matter there. It's not the edge of anything.
- If we are outside the horizon, we can see other things outside the horizon, but nothing inside.

Properties of Hades

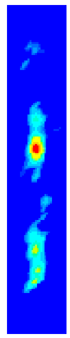
- Mass = 10 $M_{\odot}$
- Horizon circumference = 186 km
- Rotation period = infinite (it's not spinning)
- Not very much interstellar gas falls into hole; what does is accelerated to very high speeds (close to the speed of light), and emits *light*, notably X-rays and γ-rays, while it's on the way in, due to this acceleration.



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

A picture of Hades?

We know of several real black holes that are the size of Hades, but none that have so little interstellar material falling into them, and none that aren't spinning rapidly. It's very hard to see black holes from a great distance *unless* there's matter falling into them at a large rate.



This is a false-color, radio-wavelength image of GRO J1655-40. Hot material on its way into the black hole produces the point of light in the center; the other features are gas clouds *expelled* at nearly light speed after missing the black hole.
(By Bob Hjellming and Mike Rupen, NRAO.)

Exploring the neighborhood of Hades

Drop Arnold the robot into the hole, having him send laser signals back to the ship as he falls.

- Laser light shifts to longer and longer wavelength as he falls: the **Doppler shift** caused by his high speed with respect to you.
- Instead of winking out abruptly as he crosses the hole's horizon, signals keep arriving at gradually increasing intervals forever: from the outside it *looks* like it takes Arnold an infinite amount of time to cross the horizon, even though he's already fallen in (according to him).
- This is **time being warped** by the BH's gravity.
- **He *cannot* get out once he falls past the horizon**!

The electromagnetic spectrum (light)

Visible light is actually just a tiny part of the spectrum of light.

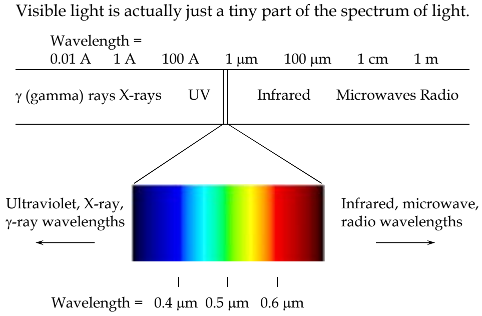
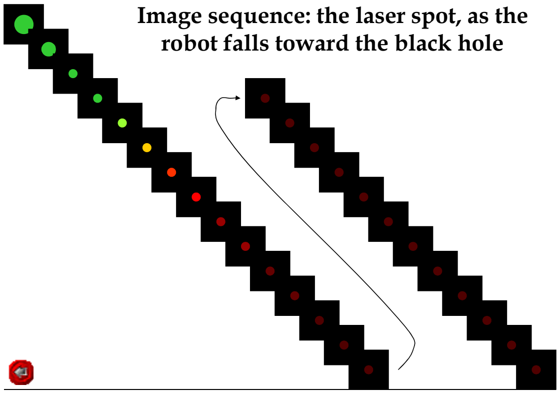


Image sequence: the laser spot, as the robot falls toward the black hole



In Arnold's view

Suppose we were also shining a green laser at Arnold as he fell. How do you suppose our laser spot looked to him?

A. Just like his did to us: gets redder ever more slowly, never winks out.

B. Gets steadily redder without bound, til the Crash.

C. Gets bluer ever more slowly, never winks out.

D. Gets steadily bluer without bound, til the Crash.

In the Earth's view

During our trip, the distance from Earth to Hades appeared to be much shorter than when we were at rest.

An observer watching from Earth would also see an element of the scene to be shorter during our trip. What?

A. The distance from Earth to Hades, just like us.

B. Our spaceship C. Hades itself D. The Earth.

Mid-lecture break.

WeBWorK homework set 1 is now available – it's due at 5:30 PM, Saturday, 12 September 2009.

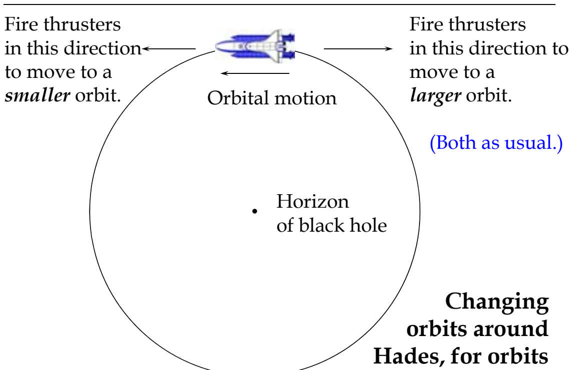
Image: barred galaxy M95. Our home galaxy, the Milky Way, would look much like this if viewed face-on from a great distance (Michael and Michael McGuiggan/Adam Block/NOAO/AURA/NSF).

Changing orbits around Hades, for orbits lots bigger than the horizon

To move from orbit to orbit, our spaceship has to obey the laws of physics: in particular the conservation of energy and orbital spin (a.k.a. angular momentum).

- ❑ Smaller-radius orbits have faster orbital speeds and higher kinetic energy (energy of motion), but lower spin.
- ❑ Thus: to move to a smaller-radius orbit one has to **put on the brakes** to reduce the spin, and **fall** toward the smaller orbit, picking up speed again without adding spin.
- ❑ Brakes, in space: fire thrusters straight ahead.
- ❑ *Vice-versa* for a larger orbit: fire thrusters straight behind.

These are the same rules that apply for spacecraft orbiting planets and stars.



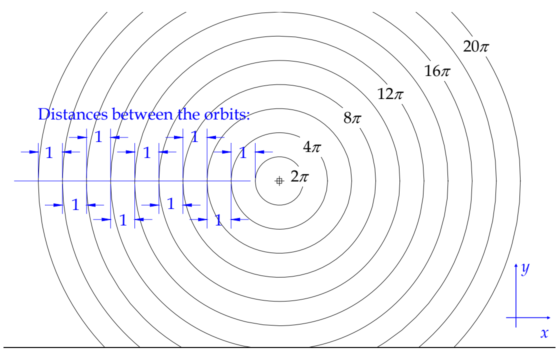
Changing orbits around Hades, for orbits lots bigger than the horizon

Exploring the neighborhood of Hades (cont'd)

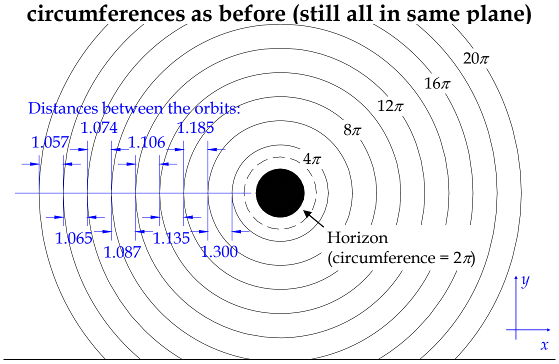
Take a capsule into orbits progressively smaller in circumference, trying to reach an orbit 1.0001 times larger than the horizon.

- As you approach the horizon, the circumference of the orbit becomes noticeably less than 2π times the radius (**warped space**: "non-Euclidean geometry").
- in 100,000 km-circumference orbit, you feel strong **tidal forces**: head and feet are pulled apart by a force one-eighth of Earth's gravity ("1/8 g").
- By 30,000 km, the head and feet are pulled apart by 4 g; by 20,000 km (still more than a factor of 100 larger than the horizon circumference), it's 15 g.
- Give up and return to the ship! We're clearly not going to make it close enough to the horizon; we need a more massive black hole.

Circular orbits in flat space (all in the same plane)

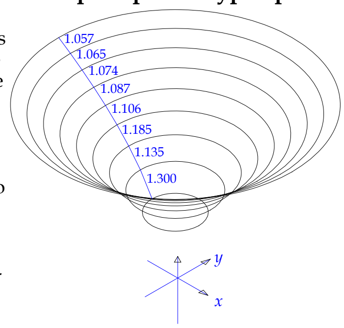


Circular orbits in space warped by a black hole, same circumferences as before (still all in same plane)



One way to visualize warped space: "hyperspace"

To connect these circles with segments of these "too long" lengths, one can consider them to be offset from one another along some **imaginary** dimension that is perpendicular to x and y but is not z. (If it were z, the circles wouldn't appear to lie in a plane!). Such additional dimensions comprise **hyperspace**.



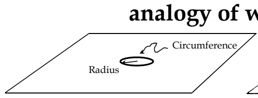
How many hyperspace dimensions?

To describe space warping in a plane (two dimensions) we have just made use of one dimension of hyperspace.

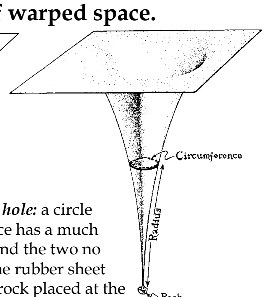
For three dimensions, like real 3-D space, how many dimensions of hyperspace would we need to describe space warping?

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

This is why one often sees 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 $C = 2\pi r$.

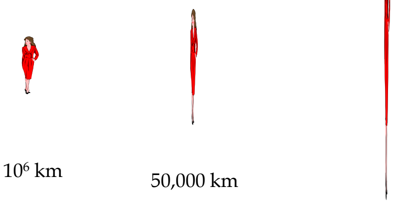


Warped space near a black hole: a circle with the same circumference has a much larger radius than before, and the two no longer obey $C = 2\pi r$, as if the rubber sheet were stretched by a heavy rock placed at the circle's center. **The direction of the stretch, though, is not in physical space, but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

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

Tidal stretching in various orbits around Hades

A body would be stretched along the direction toward the black hole, and squeezed in the perpendicular directions.



Journey to Sagittario

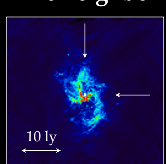
Sagittario is a black hole, a good deal less hypothetical than Hades, lying at the exact center of our Milky Way galaxy, about 30,100 light years away (actually 28,000 ly away).

- Travel in starship: acceleration = Earth's gravity again, speed close to the speed of light most of the time.
- This time the trip takes ***20*** years, measured on the starship, but ***30102*** years, measured by an observer on Earth.

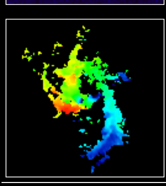
Properties of Sagittario:

- Mass = $10^6\ M_\odot$ (it's been *measured* to be $4\times10^6\ M_\odot$)
- Horizon circumference = $1.86\text{x}10^6$ km (a factor of eight larger than the Moon's orbit)
- Rotation period = infinite (it's measured to be 16 minutes)
- Again, not very much interstellar gas falls into the hole.

The neighborhood of "Sagittario" (Sagittarius A*)



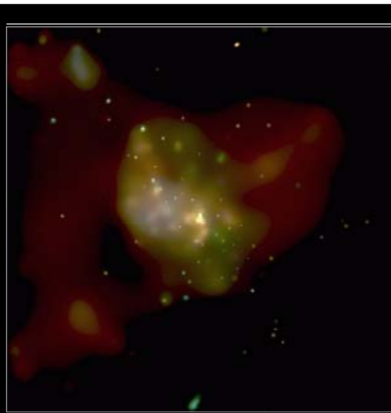
The immediate neighborhood of the black hole appears in this false-color radio-wave image as a small white dot (follow the arrows). The "swirls" are streamers of ionized gas orbiting the black hole and the star cluster that surrounds it.



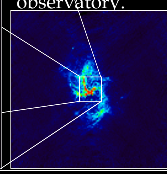
This image is a color code of the speed of the ionized gas along our line of sight. Red = receding at about 200 km/s; blue = approaching at about 200 km/s.

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

X-ray image of "Sagittario"



... by Fred Baganoff (Penn State) and colleagues, with the NASA Chandra X-ray observatory.



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Changing orbits around Sagittario, 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 has to 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 a result of the **warping of space** near the horizon, by the black hole's strong gravity.
- Orbits smaller than 3 horizons are unstable as a result:
  - 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).

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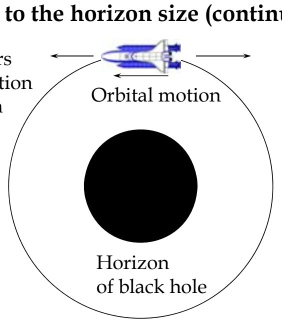
Changing orbits around Sagittario, for orbits close to the horizon size (continued)

Fire thrusters in this direction to move to a *larger* orbit. (!!!)



Fire thrusters in this direction to move to a ***smaller*** orbit. (!!!)

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Exploring the neighborhood of Sagittario

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 BH's gravitational pull with thrust instead of centrifugal force.
- Calculations: hovering at 1.0001 horizon circumferences takes a thrust of 150*g*! Better find a *more* massive BH.