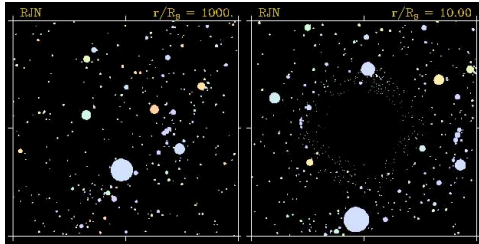


Astronomy 102

September 8, 2005: Let's go to a black hole



Too Close to a Black Hole , Credit & Copyright: Robert Nemiroff (MTU)

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Astronomy 102

Homework - WeBWork

- The Astronomy 102 homework assignments can be accessed electronically via the "Other Links - Homework Link" on the Astronomy 102 home page.
- The homework system will provide you with immediate feedback on your solutions.
- Two sets are available right now:
 - Set 0: practice WeBWork set.
 - Set 1: First homework assignment, due on Friday 9/16 at 8.30 am.

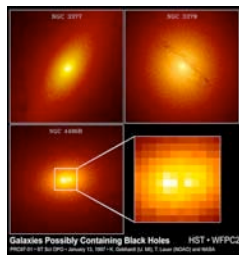


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Let's go to a black hole!

Where do we find them?

- Do all galaxies have black holes at their centers?
- Results from instruments such as the Hubble Space Telescope indicate that most large galaxies may harbor a black hole.
- In all the galaxies studied, star speeds continue to increase closer the center. This indicates that the center is millions of times more massive than our Sun.
- This mass, combined with the size of the center, suggests the existence of a black hole.



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Let's go to a black hole! Where do we find them?

Note:
Dark nebula
are unrelated
to black holes.



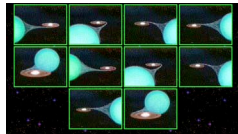
Photograph by David
Malin,
Anglo-Australian
Observatory.

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Let's go to a black hole!

- A black hole is a massive object from which nothing can escape.
- In the next few lectures we will carry out, in our heads, a trip to several black holes.
- When we travel to black holes, we will experience many unusual effects. These effects have a significant impact on life in the vicinity of a black hole.
- We will summarize the effects we encounter, but most will not be explained until later in the semester.



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Let's go to a black hole! First stop .. Hades

- Suppose a black hole exist close to Vega. Let's call this black hole Hades and let's explore its properties.
- The distance from earth to Hades is 26 light years.
- The acceleration of the space ship is +g during the first half of the trip, and -g during the second half of the trip.
- During most of the trip to Hades, we will be traveling close to the speed of light.



D. Moffatt (DOA), ScienceWeb,
Starry Messenger Communications

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Let's go to a black hole! First stop .. Hades

- Observation 1:

" Although we continue to accelerate, we never exceed the speed of light! "

- Conclusion 1:

" Nothing traveling through physical space can go faster than the speed of light. "



Liftoff of Space Shuttle Columbia
Credit: STS-1, NASA

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Let's go to a black hole! First stop .. Hades

- When you arrive at Hades, you determine that it took you only 6 years to get there.

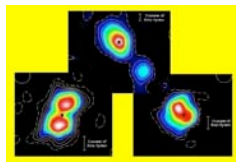
- During these 6 years, your brother on earth celebrated 26 birth days.

- Observation 2:

" Time ticks slower in a moving starship. "

- Conclusion 2:

" The distance to Hades looks shorter from a moving starship, compared to the distance observed by an observer at rest. "



Three Dusty Stars
Credit: W. Holland (JAC) et al.

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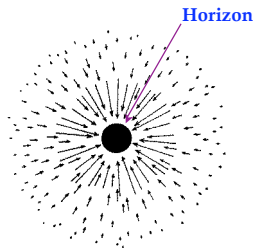
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Let's go to a black hole! First stop .. Hades

- After we get into orbit around Hades we can determine its mass from the radius of our orbit and our velocity. We conclude that Hades has a mass of 10 solar mass unit.

- The theory of relativity tells you that the circumference of the horizon must be 18.5 km times the mass of the black hole.

- For Hades, the circumference of the horizon of Hades must be 185 km. You confirm this!!!



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

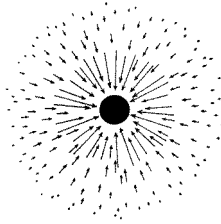
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Let's go to a black hole! First stop .. Hades

• So far we have concluded:

- Mass of Hades is 10 solar masses
- All mass is contained within the horizon of Hades.
- If the mass of Hades would be distributed uniformly within the horizon, the density would be 200,000,000 tons per cubic cm (about 200,000,000,000,000 times the density of water).
- General relativity predicts that all mass is concentrated in the center of the black hole.



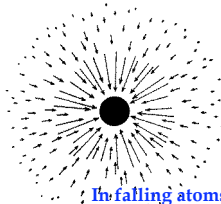
(Figure from Thorne, *Black holes and time warps*)

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Let's go to a black hole! First stop .. Hades

- Next you study the pattern of the gas atoms that fall into Hades.
- Their motion appears to be directly directed towards the center of the black hole.
- This observation tells you that Hades is not spinning. If Hades would be spinning, the flow of gas would show a tornado-like motion.
- The gas atom accelerated when they approach Hades and emit gamma-rays and X-rays.



Infalling atoms of interstellar gas

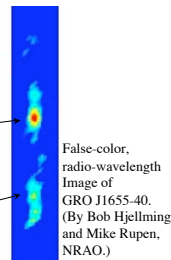
(Figure from Thorne, *Black holes and time warps*)

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Let's go to a black hole! First stop .. Hades

- Most black holes that are similar in size to Hades are spinning rapidly and have lots of interstellar material falling into them.
- The material falling into the black hole emit radiation that we can detect.
- A fraction of the material misses the black hole and are expelled with a speed close to the speed of light. They also emit radiation which can be detected.



False-color, radio-wavelength Image of GRO J1655-40. (By Bob Hjellming and Mike Rupen, NRAO.)

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Let's explore Hades!

- In order to explore the properties of the black hole, we decide to drop Arnold, a cousin of 3CPO, into the black hole.
- During his descent, Arnold will send pulses of laser light back to our ship, containing information such as his altitude.
- By examining the wavelength of the laser light you can determine Arnold's velocity. This shift in wavelength is known as the Doppler shift.

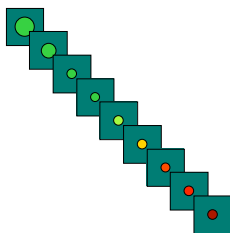


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Let's explore Hades!

- The light emitted by Arnold is shifted to longer wavelengths.
- Instead of disappearing abruptly as Arnold crosses the hole's horizon, the 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. However, this is a result of the fact that it takes longer and longer for the signals to escape the gravitational grip of the hole.

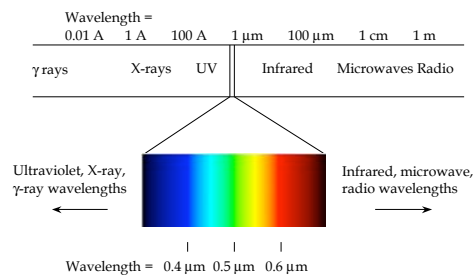


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Doppler Shifts Shifting wave lengths

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



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Doppler shifts: the shift in wavelength is related to the velocity of the source!



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Astronomy 102 Mid-Lecture Break

• Reminders:

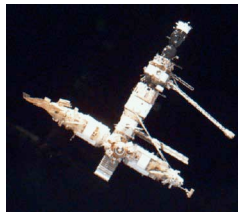
- You can now sign up for the recitations. Go to the Astronomy 102 homepage and click on the "Recitation Signup" link.
- Make sure you try homework set 0 in the next few days to make sure you can connect. You do not want to wait until next week Friday 3 am to find out that your information is not in the data base.



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Let's explore Hades! We go ourselves!

- In order to explore Hades ourselves, we will slow our space ship down to reduce the size of our orbit.
- Each stable orbit has a specific velocity associated with it. By controlling the velocity, we can control the radius of the orbit.



Atlantis Approaches Mir
Credit: NASA, STS-76 Crew

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

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

Orbital motion

Horizon of black hole

Changing orbits around Hades

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Let's explore Hades!
We go ourselves!

- In normal "Euclidean" space, the circumference of an orbit is proportional to the radius of the orbit.
- When the radius of the orbit changes by Δr in "Euclidean" space, the circumference changes by $2\pi(\Delta r)$.
- However, near Hades we find that this is no longer true, and instead the circumference is less than $2\pi r$. We have entered warped space; we have entered a "non-Euclidean" world or hyper space.

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Let's explore Hades!
Entering hyperspace!

- Some properties of hyperspace can be envisioned if we consider the "rubber sheet" analogy.
- A light rock will keep the rubber sheet flat, and the circumference of a circle around the rock will be $2\pi r$.
- A massive rock will distort the rubber sheet, and the circumference of the circular orbit will be much smaller than $2\pi r$, if r is defined as the distance to the rock.

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

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Let's explore Hades! Entering hyperspace!

- Besides being amazed by the break down of basic geometrical rules, you start to feel the effect of hyperspace on your body.
- The gravitational field around Hades is responsible for pulling your feet towards Hades, while your head is being tugged upwards; you are being stretched!
- Forces involved:
 - 80,000 km: 1/4 g
 - 50,000 km: g
 - 30,000 km: 4 g
 - 20,000 km: 15 g Let's go!



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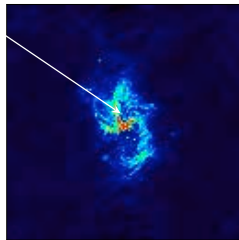
Let's forget about exploring Hades! Leaving hyperspace!

- At 20,000 km, the stretching force becomes so large that it does not make any sense anymore to continue, if we have the desire to survive our trip.
- The tidal forces generated by the black hole are proportional to the ratio of the mass of the hole and the cube of its circumference of its horizon.
- Since the circumference of the horizon is 18.5 times the mass of the black hole, we conclude that the tidal forces are proportional to the mass/(18.5 mass)³. Thus, if the mass of the black hole increases, the tidal forces decrease by a factor of mass².

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Let's explore Sagittario

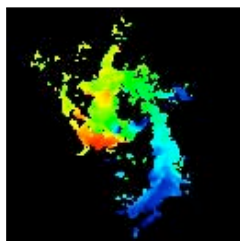
- Sagittario is a massive black hole at the center of our galaxy.
- The distance from Hades to Sagittario is 30,100 light years.
- The mass of Sagittario is 10⁶ solar mass units.
- Based on our experience at Hades we expect:
 - The circumference of its horizon is 1.85 x 10⁶ km.
 - The tidal forces around Sagittario should be 10,000,000,000 times weaker than the tidal forces around Hades.



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Let's explore Sagittario

- This image of the region around Sagittario 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
- The pattern of the gas falling into the black hole indicates that it is not spinning. The amount of material is also small.



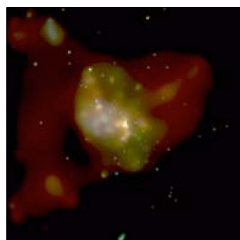
Data: D. Roberts and M. Goss (1993), using the NRAO Very Large Array radio telescope.

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Let's explore Sagittario

- In order to reach Sagittario we travel with a constant acceleration of $+g$ for the first half of the trip and $-g$ for the second half of the trip.
- The trip to Sagittario takes 20 years, as measured by our clocks. However, an observer on earth determines that it took 30,102 years to reach Sagittario.



X-ray image of Sagittario
Baganoff et. al.

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Let's explore Sagittario!

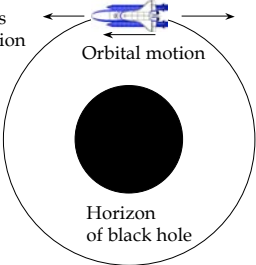
- Our goal: to take a capsule into orbits progressively smaller in circumference, trying to reach an orbit 1.0001 times larger than the horizon again.
- We know:
 - Tidal forces are bearable in orbits as small as 1.5 times the horizon circumference.
- We observe:
 - For orbits 3 times the horizon circumference and smaller, the thrust has to be applied *backwards* to have the desired effect on orbital changes. Orbits are unstable as a result.
 - 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."
 - Calculations: hovering at 1.0001 horizon circumferences takes a thrust of 150g! Better find a *more* massive BH.

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Let's explore Sagittario
What is happening at small orbits?

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



Orbital motion

Horizon
of black hole

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

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Let's explore Sagittario!
What is happening at small orbits?

- Our understanding of orbital motion, and how to change orbits, relies on Newtonian mechanics.
- Many effects in astronomy and space travel can be accurately described in terms of Newtonian mechanics.
- However, Newtonian mechanics starts to break down when the speed of objects approach the speed of light or when the gravitational forces become enormous.
- Einstein's theory of general relativity describes the behavior of objects at high speed or in strong gravitational fields with great accuracy.
- Einstein's theory of general relativity can in fact describe the behavior we observe around Sagittario.

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Let's try to explore even more massive black
holes the next time we meet!



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