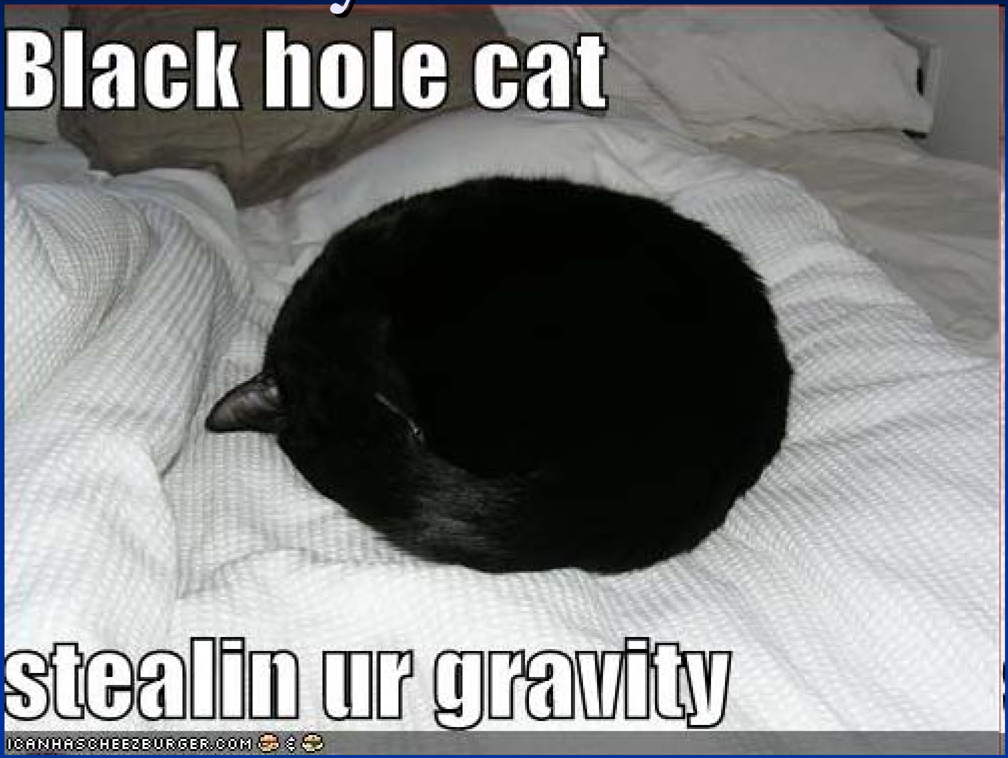
Compton Lecture #8: Fade to Black: Black Holes and X-Ray Binaries



- Welcome!
- On the back table:
  - Lecture notes for today's lecture
  - Extra copies of last week's are on the back table
  - Sign-up sheets
    - please fill one out only if you're not already on the Compton Lectures mailing list or need to change your address

Stars: Their Life and Afterlife

Fade to Black: Black Holes and X-Ray Binaries

Brian Humensky

68th Series, Compton Lecture #8

December 13, 2008

Outline

- Black Holes
- The Galactic Center
- X-Ray Binaries
- TeV Gamma-Ray Binaries

Key Points to Take Away

- Black Holes are among the simplest and most exotic phenomena in nature.
- Black Holes are revealed by their interactions with gas and stars.
  - Orbital dynamics provide strong indirect evidence for existence of Black Holes.
    - Supermassive Black Holes in centers of galaxies
    - Stellar-mass Black Holes in binary systems
  - Current / future missions will test general relativity in detail near the event horizon.
- X-ray and Gamma-ray studies of binaries are testing General Relativity and revealing physics of accretion disks, jet formation, particle acceleration and more.

Black Holes

What is a Black Hole?

- An object whose gravity is so strong that nothing – not even light – can escape.
- Described by 3 properties:
  - Mass
  - Electric charge (usually 0 or thereabouts)
  - Angular momentum
- "simplest macroscopic objects in nature"

What is a Black Hole?

- An object whose gravity is so strong that nothing – not even light – can escape.
  - Defining characteristic of a Black Hole: possesses an **event horizon**.
- Other general relativistic phenomena are not unique to Black Holes:
  - gravitational redshift, bending of light, last stable circular orbits, dragging of inertial frames all present in (at least some) other objects.
- What it's NOT: the ultimate vacuum cleaner.

How Massive is a Black Hole?

- In principle, any mass!
- In practice:
  - From stellar core collapse, mass range ~ 3 – 20 $M_\odot$
  - Cores of galaxies have Supermassive Black Holes ~ millions – billions $M_\odot$
    - Formed by mergers / sweep-up of matter over billions of years
  - Intermediate masses???

How Big is a Black Hole?

- Size defined by radius of **event horizon**:
  - for a non-rotating Black Hole, it's a simple formula

$$R_g = 2GM / c^2$$

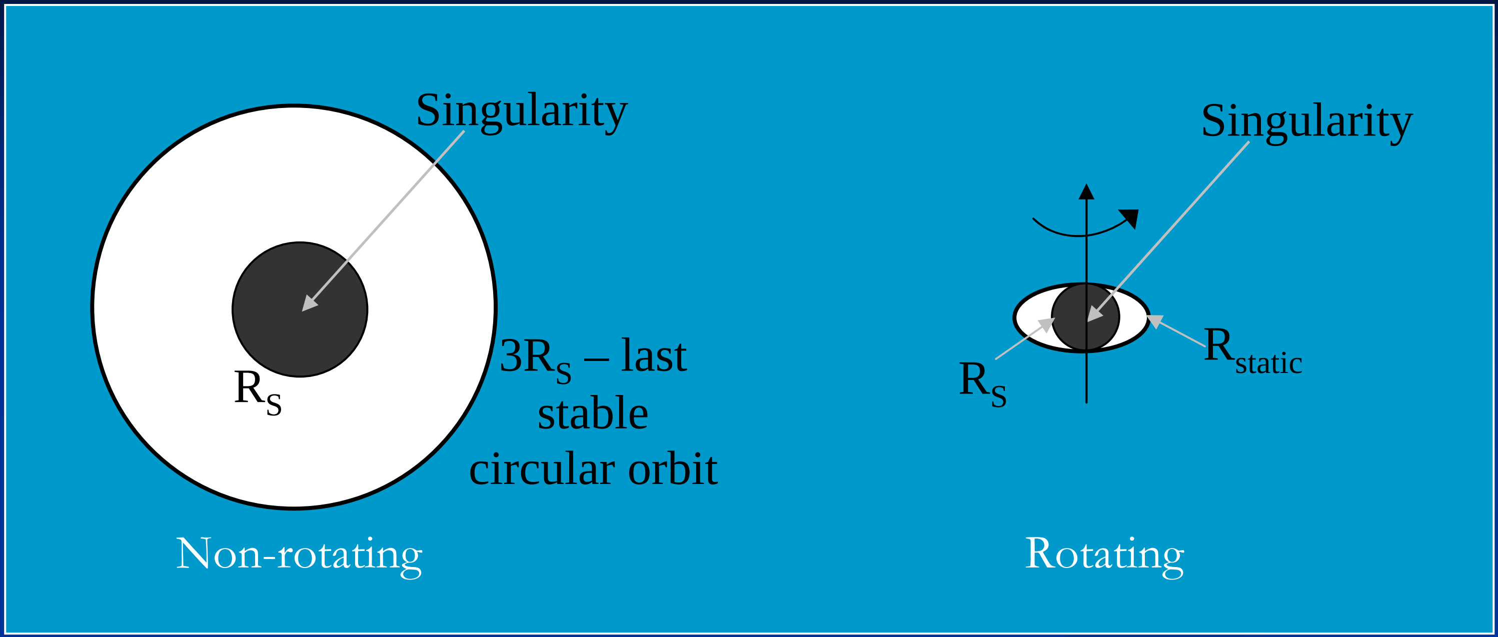
  - reduces to

$$R_g = 3 \, M / M_{\Theta} \text{ km}$$

Black Holes Compared to …

Object	***Radius***
Solar-Mass Black Hole	**1.5 - 3 km (depending on spin)**
Neutron Star	~10 km
White Dwarf	~10,000 km (~Earth size)
Sun	700,000 km
Sgr A* (galactic center)	**~10 million km**
Giant Branch Stars	~300 million km (Earth's orbit)
Supergiant Stars	~1.6 billion km (Jupiter's orbit)

Diagram of a Black Hole



- Singularity "hidden" inside event horizon
- Black Holes have a last stable circular orbit
  - Because kinetic energy of orbit ADDs to gravitational attraction
- Spinning black holes are smaller than stationary black holes
  - Probe deeper into gravity well.

Forming Stellar-Mass Black Holes

- Two mechanisms in core collapse of massive stars:
  - Fall back of matter onto proto-neutron star core after supernova
    - If explosion not able to unbind entire stellar envelope, remainder will be pulled back
    - Maximum neutron star mass is ~ 2-3 $M_\odot$
  - Direct collapse to black hole (no supernova)
    - If core too massive when collapse begins, can collapse to a Black Hole in < 1 second
- How many? Perhaps 10^7 – 10^9 Stellar Mass BHs in Milky Way.
  - Most isolated – hard to see!

Do Black Holes Really Exist?

- To date, most evidence is indirect – but compelling
  - Measurements made far from event horizon, where gravity is "Newtonian"
    - Orbital dynamics near Galactic Center
    - Orbital dynamics, rapid variability of X-ray binary systems
- Now and future: goal to probe region near event horizon
  - Where distinctly general relativistic phenomena occur

The Galactic Center

OK – one supermassive black hole

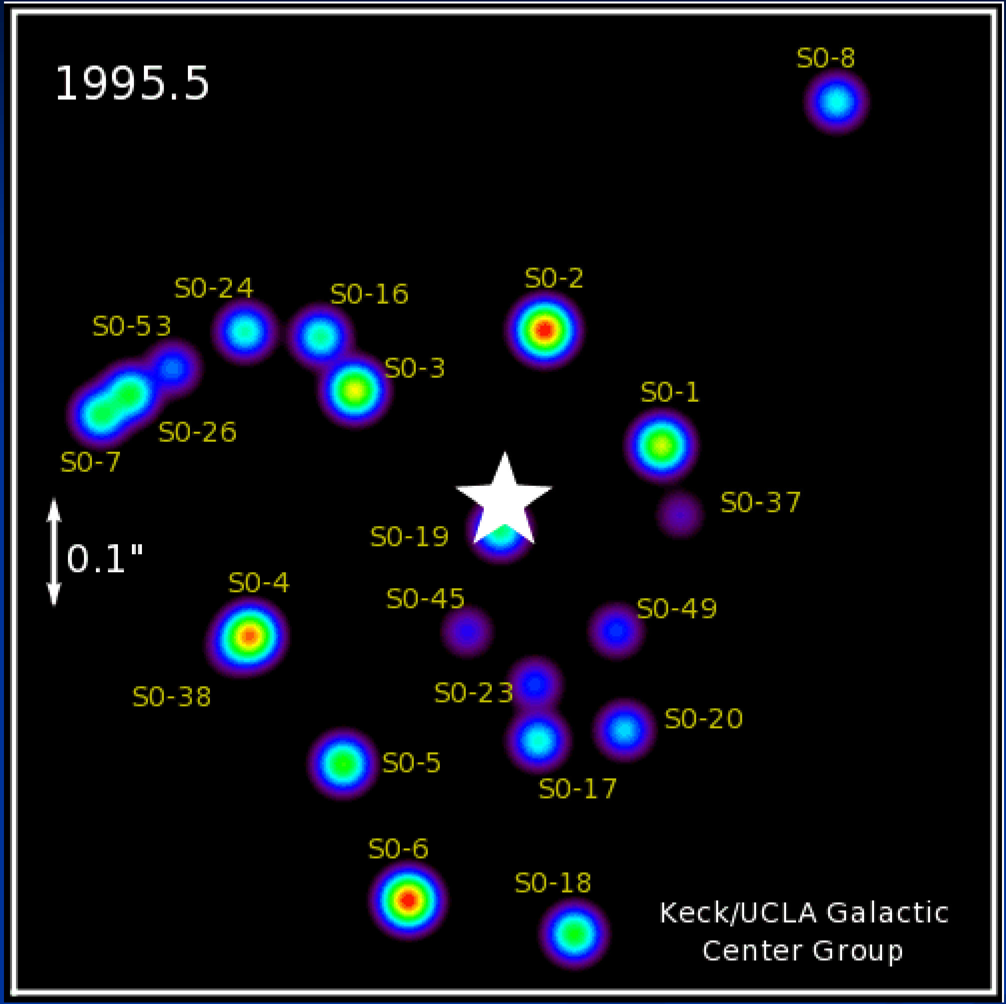
(but only because it's so important)

Sgr A*: The Milky Way's Supermassive BH

- Measuring the paths of stars about the Galactic Center and applying Kepler's Laws tells us they are orbiting an enclosed mass of $4.3 \cdot 10^6 \, M_\odot$ ± few %.
  - Compare to mass of galaxy: $\sim 6 \cdot 10^{11} \, M_\odot$
- The nearest star passes within ~1000 R_S (45 a.u.) of the central object.
- Only a Black Hole explains such a large mass within such a small region.
- Two research groups, working since early/mid 1990's.
  - Keck/UCLA and MPI-Garching.

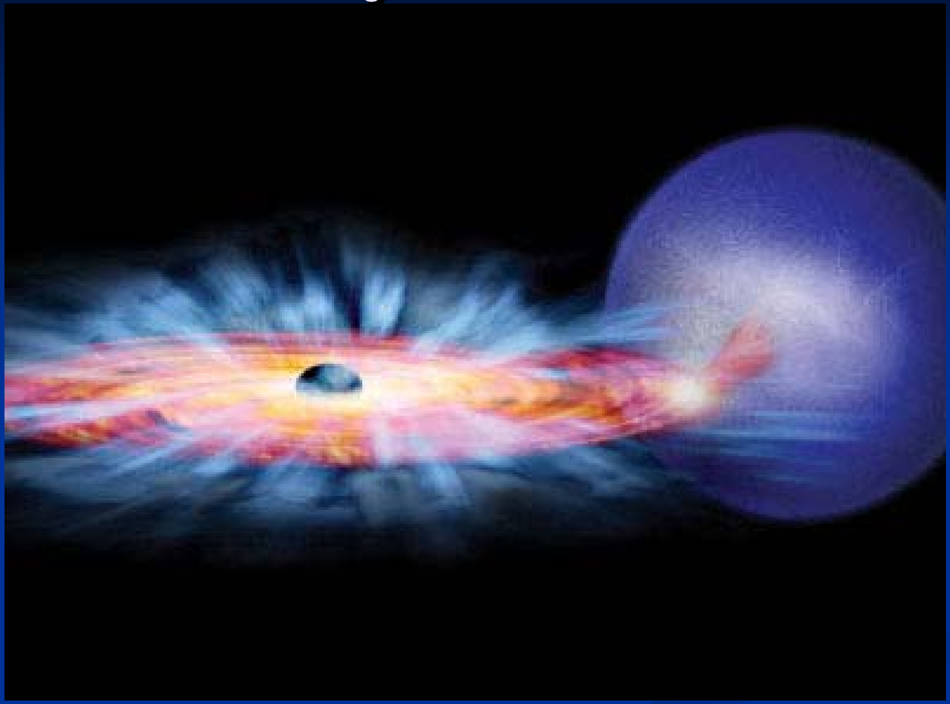
Sgr A*: The Milky Way's Supermassive BH

- Images from 1995-2008.
- Track specific stars, calculate orbits.
  - All agree!
- Key stars:
  - SO-2, period 15.56 yrs ~complete orbit measured!
  - SO-16, approaches within 45 a.u. of Black Hole!
- Mass = $4.3 \cdot 10^6\ M_\odot$ ± few % (MPI-Garching).
- Many other galaxies also appear to have supermassive black holes at their centers.



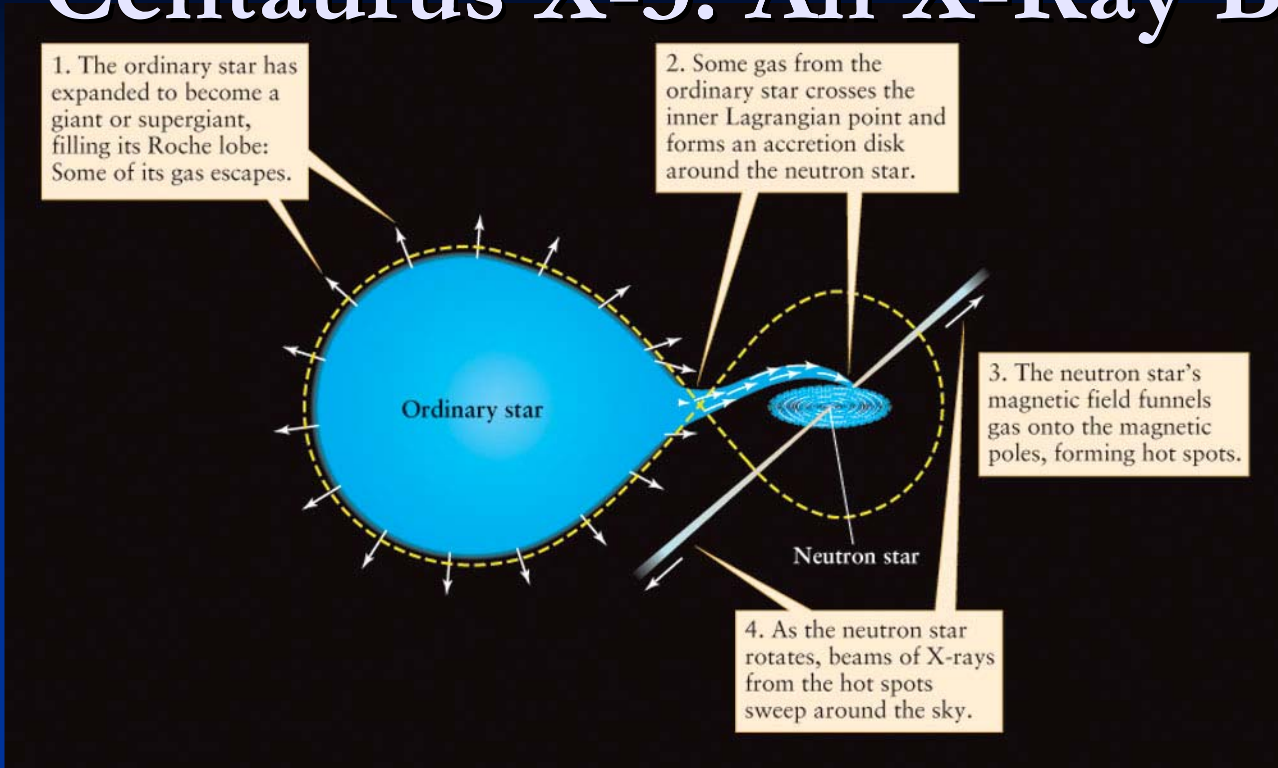
X-Ray Binaries

X-Ray Binaries

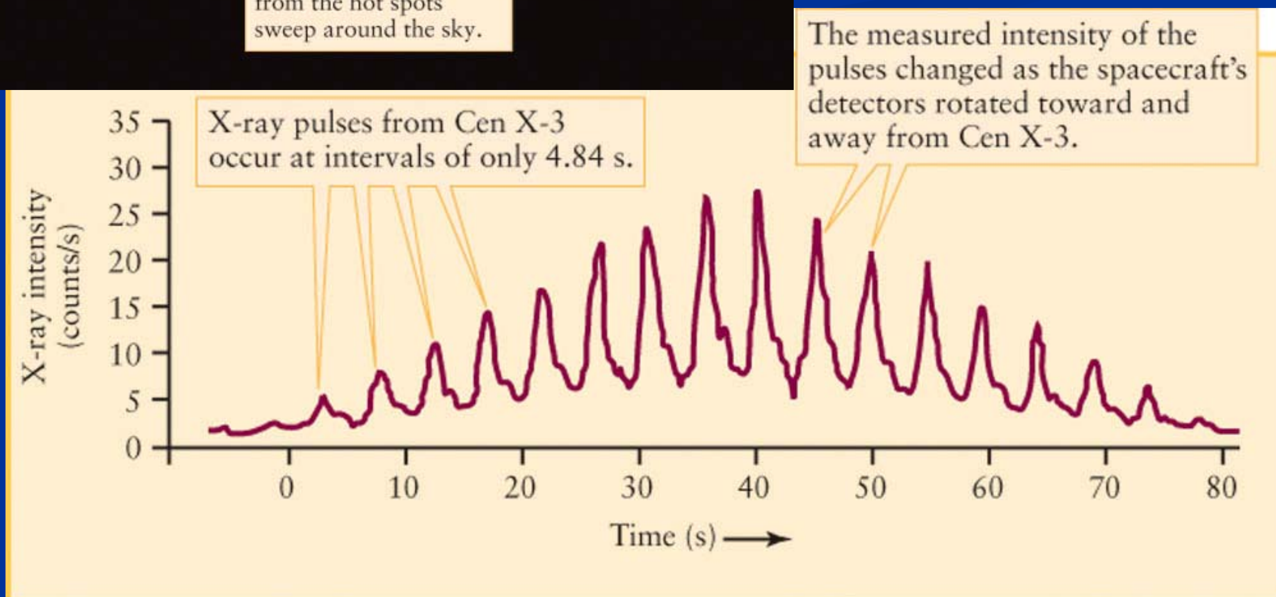


- Ordinary star plus compact object – Black Hole or Neutron Star
- X-ray emission powered by accretion
  - mass transfer from star to compact object

Centaurus X-3: An X-Ray Binary Pulsar

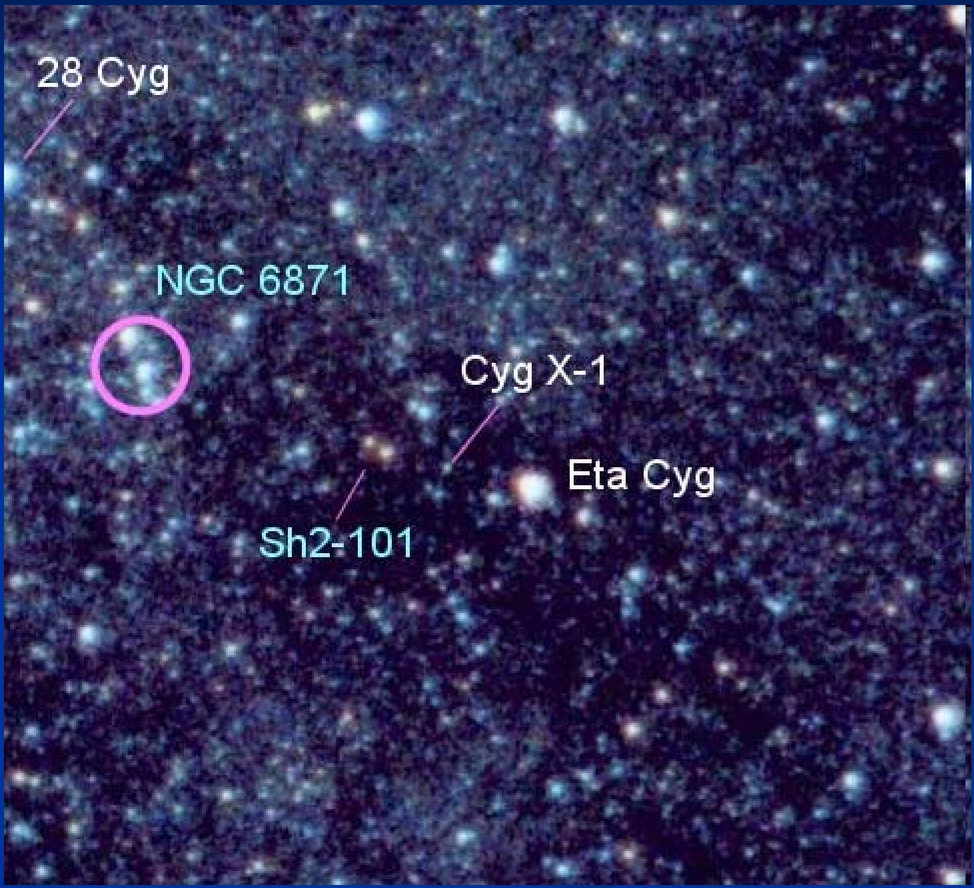


- Neutron star and ordinary star in 2-day orbit.
- Gas from star is slams into NS's magnetic poles, heats surface to 100 million K.
- Forms intense X-ray pulsar, emitting 10^{31} W!
- 100,000 * Sun's luminosity.

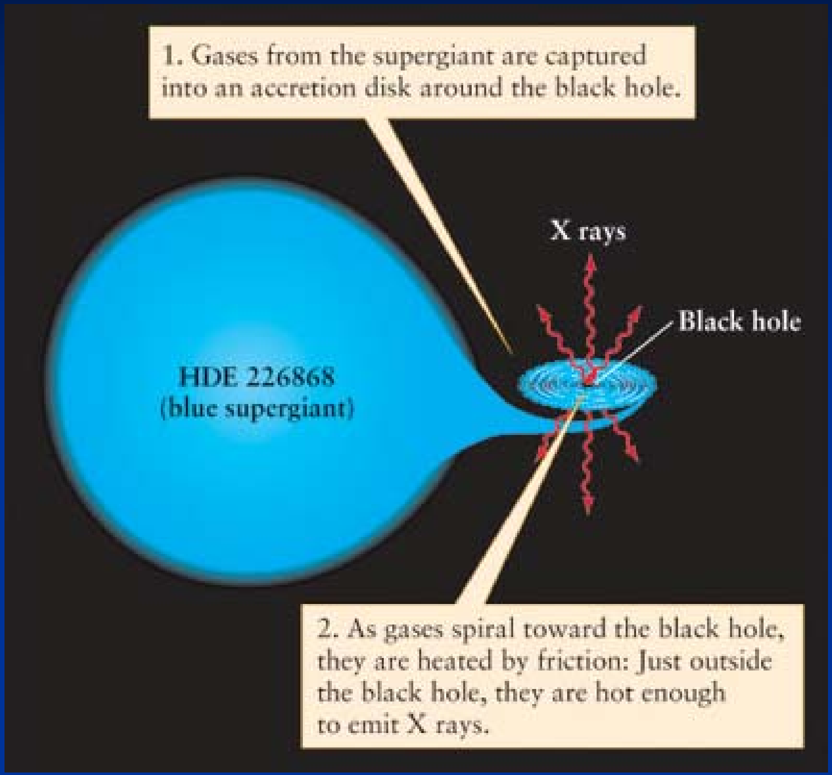


Cygnus X-1: A Black-Hole Binary

- High-mass X-ray binary
- Visible star is a blue supergiant, ~ 30 $M_{\odot}$.
- Invisible companion has a mass ~ 5-10 $M_{\odot}$.
  - Inferred from "wobble" in supergiant's spectrum
  - Too big to be a neutron star ⇒ Black Hole by elimination
- Orbit period 5.6 days
- No associated SNR
  - Direct collapse?



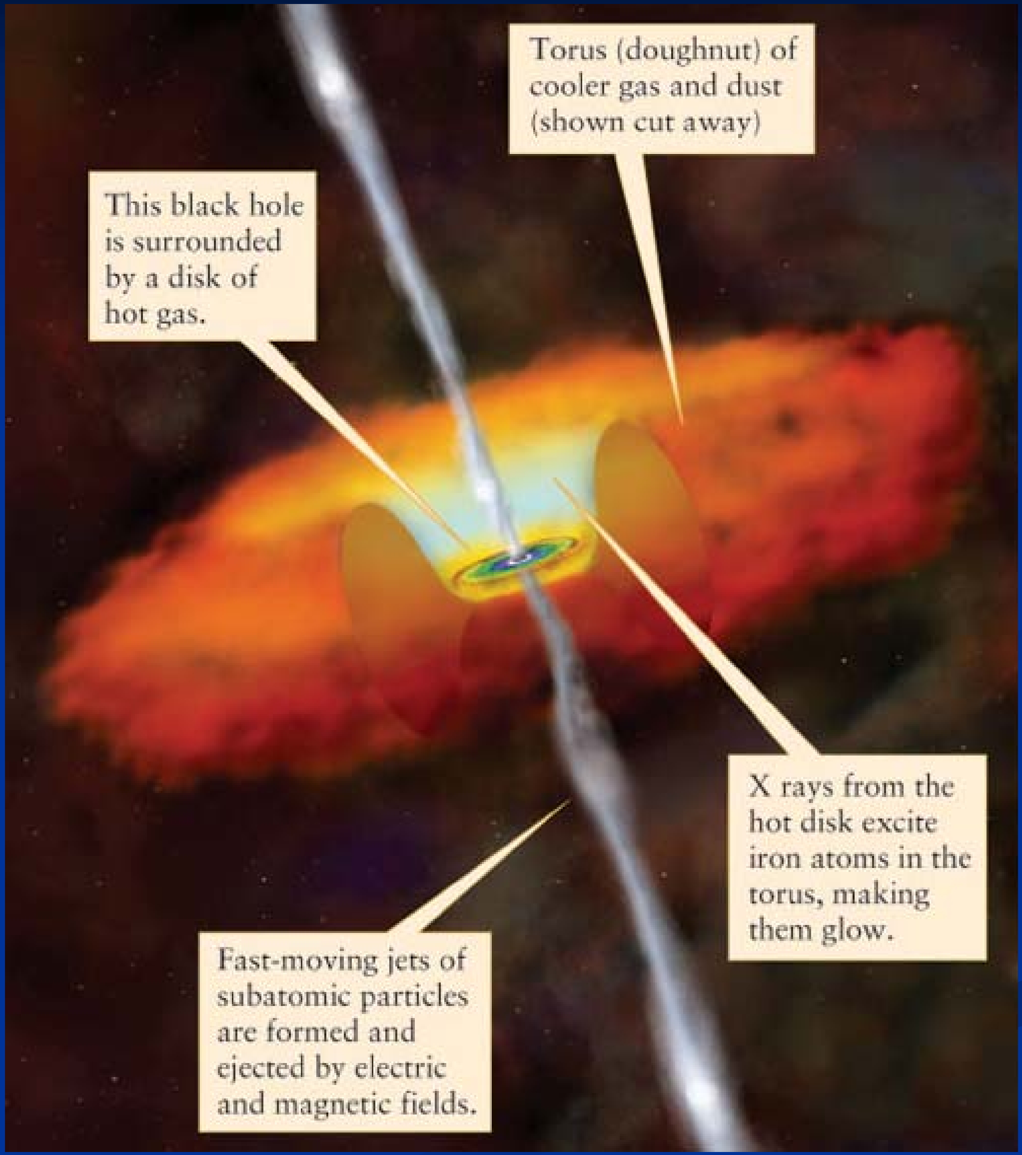
Cyg X-1: A Typical X-Ray Binary



- Close orbit – BH distorts star's shape via tides
  - Matter is sucked off star and forms a disk around Black Hole
  - But… no surface to slam into!

Accretion Power

- Accretion disk forms around Black Hole.
- Gas spirals towards BH, accelerates and compresses
  - heats to millions of degrees ⇒ emits intense X-rays.
- Disk is "clumpy" ⇒ X-ray flux varies with time.



How Powerful is Accretion?

- Comparison: Stars resist gravity via fusion: most efficient fusion reaction is 4 p → ^{4}He – liberates **0.7%** of rest mass.
- Accretion: convert gravitational potential energy → kinetic energy and heat → radiation.
- Neutron stars: gas can reach ~ 50% speed of light.
  - Energy released equivalent to **~ 10%** rest mass.
- Black Holes: Infalling matter can radiate efficiently until it reaches last stable circular orbit.
- Accretion onto Black Hole depends on spin:
  - **~ 6%** for non-rotating BHs
  - **~ 40%** for maximally rotating BHs

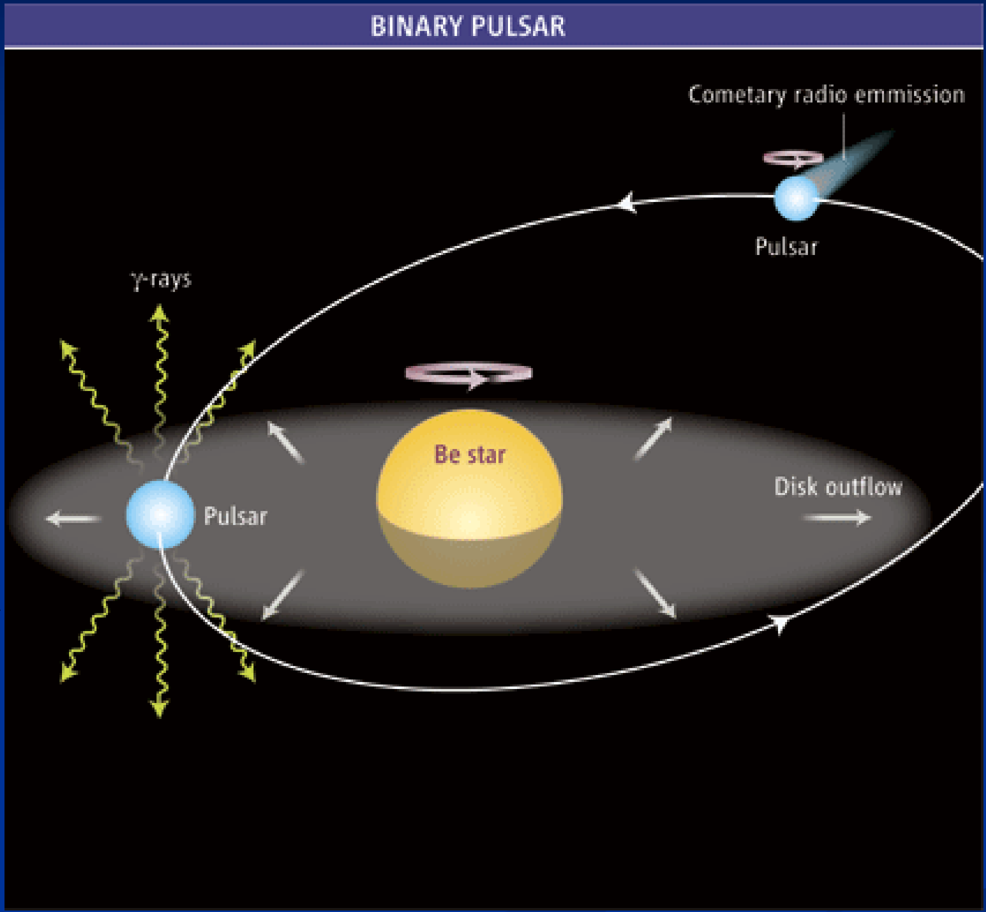
TeV Gamma-Ray Binaries

Pulsar Binaries

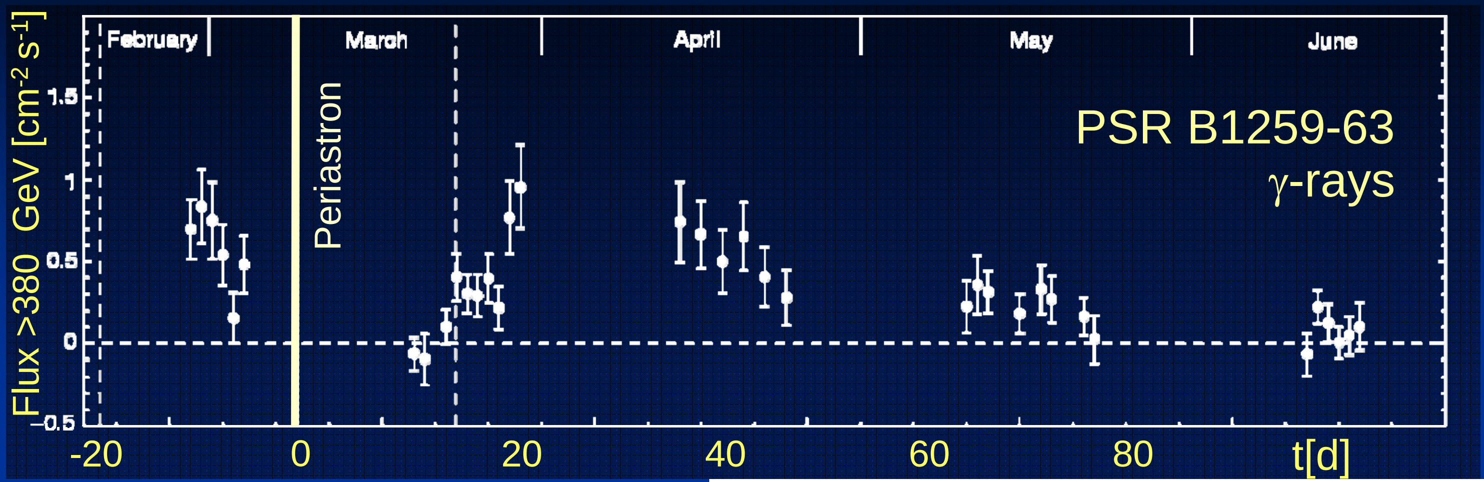
Microquasars

Binary Pulsars and TeV Gamma Rays

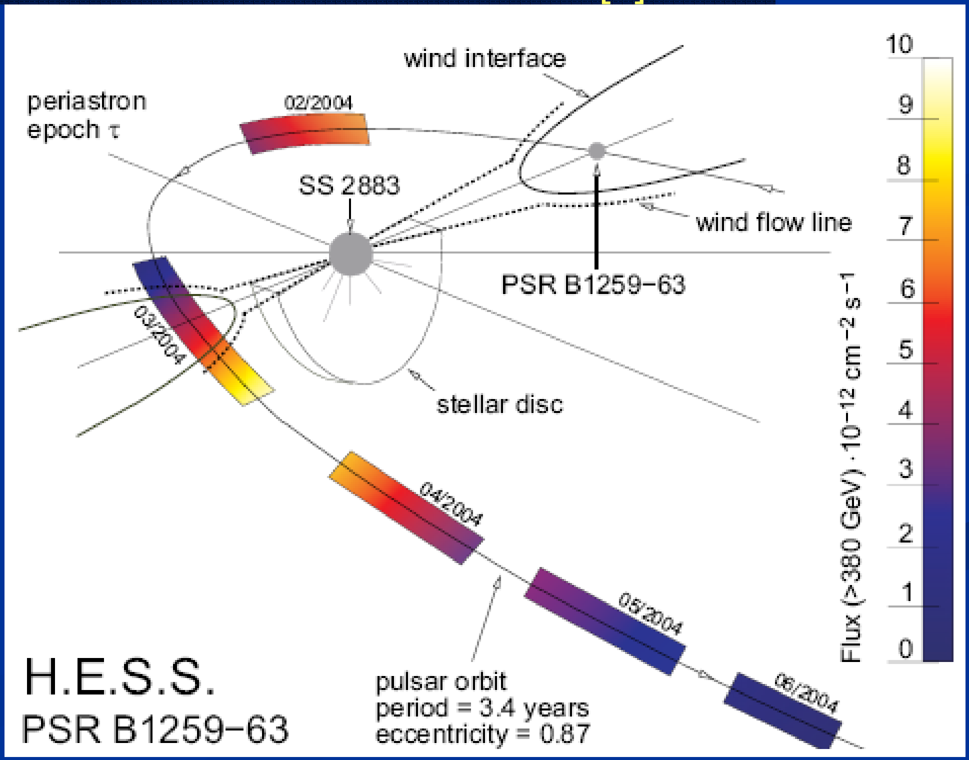
- Pulsar / massive star binary systems
- Particle acceleration when winds from pulsar and massive star collide.
  - Properties of shock front vary during orbit
  - Beautiful laboratory to compare with magnetohydrodynamical simulations, calculations



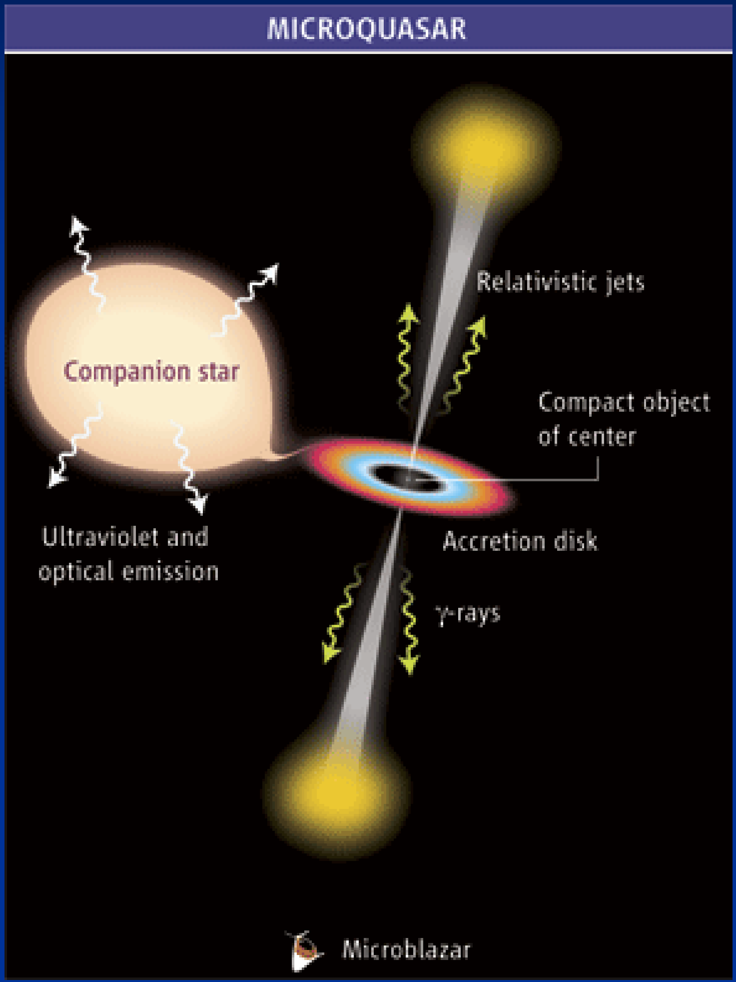
HESS Observations of PSR B1259-63



- Pulsar in a 3.4-yr orbit around a massive star.
- HESS observed during and after closest approach in 2004.
- Particle acceleration in wind interactions during closest approach!



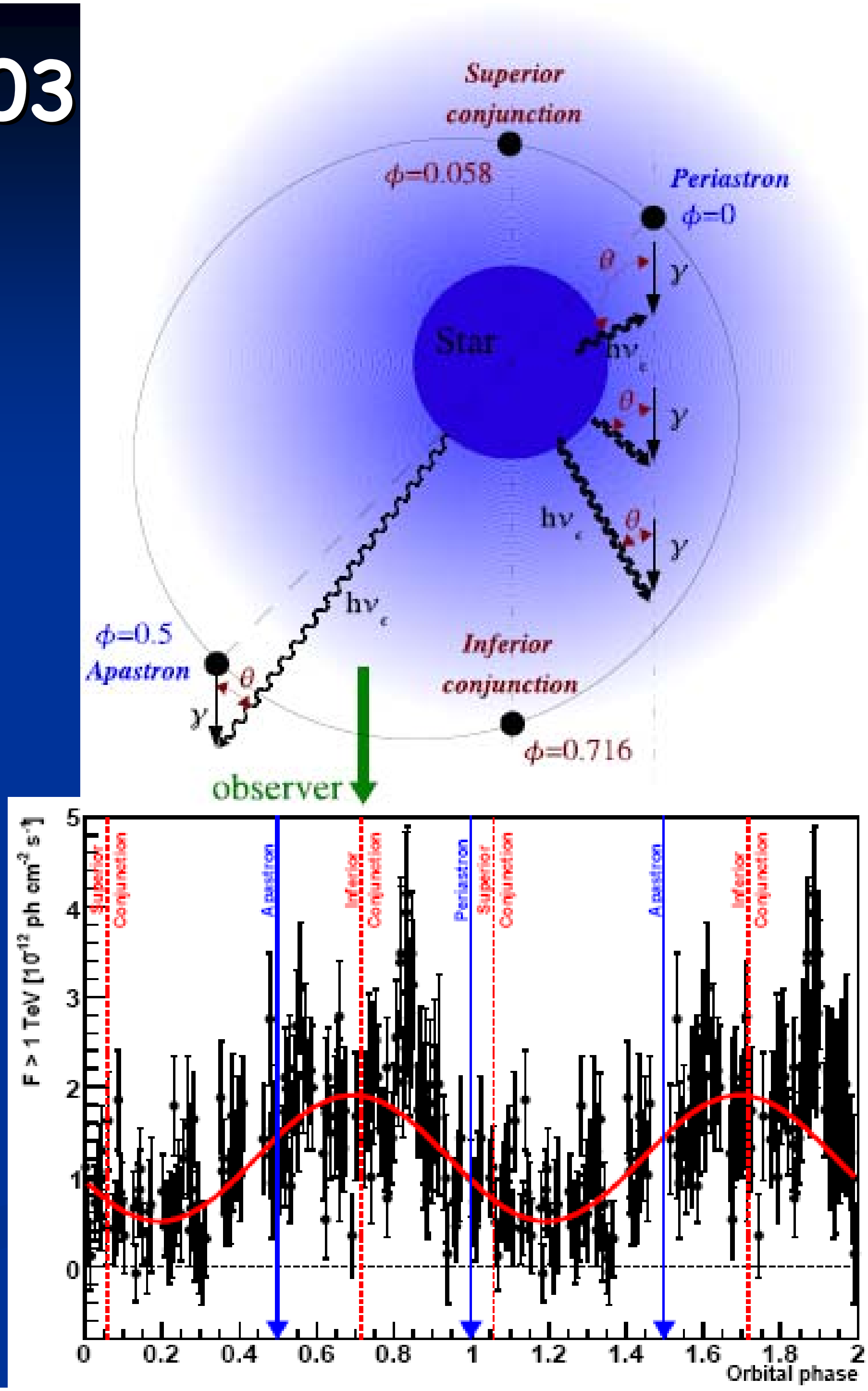
Microquasars and TeV Gamma Rays



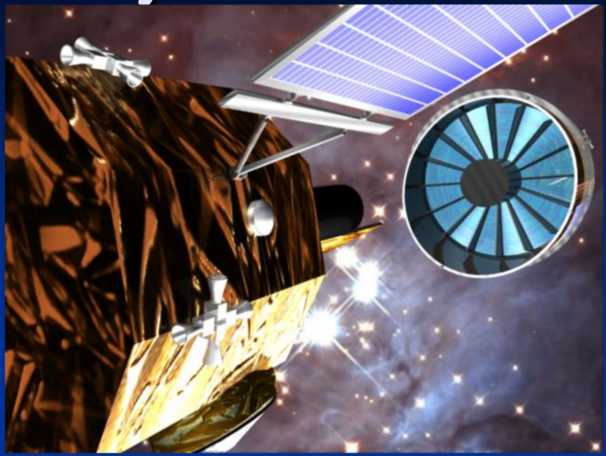
- Microquasar: compact object has beams ("jets") of accelerated particles coming out perpendicular to accretion disk.
  - Similar to the Quasars we see in distant galaxies, only smaller.
- TeV gamma rays can tell us
  - How much energy is in the jets compared to the disk
  - Composition of jets (protons? electrons?)

LS 5039 & LS I +61 303

- 2^{nd} and 3^{rd} TeV Binaries discovered
  - Black Hole vs Neutron Star? Unclear
    - could be microquasars or binary pulsars
- LS 5039: First measure of orbital modulation in TeV gamma rays: 3.9-day period
  - Highest flux when compact object between us and star
  - gamma production / absorption modulated
- LS I +61 303: 26-day orbital period
  - X-ray, TeV fluxes show orbital modulation, but fluxes vary orbit-to-orbit



The Future: Black Holes as Strong Gravity Laboratories



- International X-ray Observatory
  - 10-100x more powerful than existing X-ray satellites
  - Test predictions of General Relativity near Black Hole and Neutron Star surfaces
- LIGO / LISA – gravity wave observatories
  - Search for signals from Black Hole mergers, formation events
- Current / future Gamma Ray telescopes
  - Study energetics of accretion disk / jet systems, particle acceleration in jets and colliding winds

Summary

- Black Holes are among the simplest and most exotic phenomena in nature.
- Black Holes are revealed by their interactions with gas and stars.
  - Orbital dynamics provide strong indirect evidence for existence of Black Holes.
    - Supermassive Black Holes in centers of galaxies
    - Stellar-mass Black Holes in binary systems
  - Current / future missions will test general relativity in detail near the event horizon.
- X-ray and Gamma-ray studies of binaries are testing General Relativity and revealing physics of accretion disks, jet formation, particle acceleration and more.