Lecture 28

Black Hole Remnants
Binary Star Evolution
Observing Black Holes

*Schwarzschild Radius*

*Novae*

*X-Ray Binaries*

*Accretion Power*

Black Holes

- Neutron stars are already very close to \( v(\text{escape}) = c \). If mass \( > 3 \, M_{\odot} \), nothing can stop it collapsing beyond that point. Then get "black hole". Description requires physics beyond Newton: special and general relativity (later). Here is the bottom line:

- If object not rotating, the resulting object is described by a single number: "Schwarzschild Radius". The radius of a sphere around a black hole of mass \( M \) from which the escape velocity is the speed of light. The Schwarzschild radius of a black hole is proportional to its mass.

\[
R(\text{Sch}) = \frac{2 \, G \, M}{c^2}
\]

Doing ratios with sun,

\[
R(\text{Sch}) = 3 \, \text{km} \times \frac{M}{M_{\odot}}
\]
Black Hole Facts

• A (nonrotating) black hole is observable only by its gravity. Everything happening inside the Schwarzschild radius is unobservable by us. For this reason, the surface defined by the Schwarzschild Radius sometimes called the "event horizon".

• Note: theoretically, you can have a black hole of any mass, if you can somehow compress it within its Schwarzschild Radius. The massive-star evolution scenario leads us to look for BH's of Mass 3 - 30 M\text{sun}.

Theoretical Properties of Black Holes

• Einstein's general relativity has been solved for all possible "static solutions" of black holes. (Forming stellar-mass BH's probably settle into these very rapidly after radiating copious "gravitational radiation").

• There are only three physical properties which define a static black hole: electric charge, mass, and angular momentum. All other internal properties (magnetic field, composition, etc) have no effect on the outside. ("Black holes have no hair").

1) Charge

• Theoretically this makes a difference, but electric force from a charged BH will quickly suck in enough opposite charged particles to neutralize it.
Black Hole Properties

2) Mass
• Near the event horizon (Schwarzschild radius):
  – Weird time effects due to general relativity. eg time appears to slow down: "gravitational redshift"
  – In stellar-mass BH's: very large "tides" so that solid material is shredded.
• Far from event horizon ( > 100 R(Sch) ~ 3000 km )
  – Looks just like gravity from an ordinary star of same mass => BH's can be detected in binary systems with ordinary stars

3) Angular Momentum
• Since neutron stars are formed with rapid spins (pulsars) this seems likely.
  – Solution called a "Kerr black hole".
  – Spacetime outside event horizon is "dragged around" by rotation.
  – It is theoretically possible to extract energy from the rotation.

Binary Star Evolution and Accretion

• In close binary, more massive star swells first, causing mass transfer onto companion: “accretion”

• Accretion disk. Gas spills into disk around gainer, heats up as it falls toward star. Temperature proportional to \(1/\text{radius to which it falls} \):
  – If white dwarf: radiates visible, UV. Get “Nova” outbursts. If mass climbs beyond 1.4 \(M_{\odot} \) implodes in Supernova "Type Ia"
  – If neutron star or Black Hole: radiates X-Ray

• Accretion power. Accretion onto very small objects is a more efficient energy source than fusion!
  – Fusion Energy - \( .007 M \ c^2 \)
  – Accretion Energy - \( M \) (infall velocity)\(^2 \)
  – black hole or neutron star infall velocity = escape velocity - 0.5 c
  – => ~ 0.25 \( M \ c^2 \)!
Observing Black Holes

Practical way involves observing the gravitational effect of a BH on its surroundings:

- In 1970, first X-Ray Satellite "Uhuru" found the **brightest X-Ray sources associated with close binary stars**.
- Some X-Rays pulsed. These must be rotating neutron stars with magnetic field driven beams.
- Some X-rays just flicker randomly. More likely black holes since BH’s can’t have magnetic fields tied to rotation causing regular pulses.

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X-Ray Binary Black Hole Candidates.

Method: process of elimination:

1) Find suspected compact objects in binary systems.
2) Find X-Ray binaries. X-rays evidence of accretion onto object smaller than white dwarf.
3) Eliminate pulsed X-Rays. These come from magnetic fields on spinning neutron stars. Black holes can't have magnetic fields.
4) Look for millisecond X-Ray "flickering": shows X-rays definitely coming from object smaller than white dwarf
5) Solve for sum of masses of two stars from doppler "velocity curve" of "normal" star. Can't get individual masses since only normal star has measurable lines.
6) (Somehow) estimate mass of "normal" star. Best if it is Main Sequence.
7) If remaining mass > 3 M_{sun}, it must be a **black hole**, since that is too massive for a neutron star.
Black Hole Candidates

The best cases so far:

• **Cygnus X-1 = HDE 226868.**
  – A 9th mag single-line 5.6-day spectroscopic binary in Cygnus. X-rays flicker.
  – Total mass from velocity curve: approximately $30 \, M_{\odot}$.
  – "Normal" star a B0I supergiant. Evolution folks say $M(B0I) < 24 \, M_{\odot}$,
  – Leaves $M(\text{compact}) > 6 \, M_{\odot}$

• **LMC X-3.**
  – Similar, but period 1.7 days.
  – "Normal" star looks like a B3V main sequence star, mass estimate believable.
  – $M(\text{compact}) > 9 \, M_{\odot}$

Future black hole detection prospects

2) **Gravitational Radiation** ("waves in space" predicted by General Relativity):

   Systems like a double neutron star binary will merge into single object too massive for neutron star.
   Merger into black hole will generate large, recognizable gravitational radiation signal.
   The Laser Interferometric Gravitational Wave Observatory (**LIGO**) on line since 2003 might see 1 of these per year.

3) Objects of galactic mass $M > 10^7$ have nothing supporting them against collapse but angular momentum.
   In some galaxy scenarios large BH's can form in center of galaxies.
   Two classes possibly observed (later for this).

4) Hypothetical: microscopic BH's formed in Big Bang
Nova Persei 1901
X-ray Binary

Gravitational Waves
Laser Interferometric Gravitational Wave Observatory (LIGO)