Lecture 23: Black Holes Readings: Sections 24-3, 24-5 through 24-8

Key Ideas

Black Holes are totally collapsed objects Gravity so strong not even light can escape Predicted by General Relativity Schwarzschild Radius & Event Horizon Find them by their Gravity X-ray Binary Stars Black Hole Evaporation via Hawking Radiation

Gravity's Final Victory

A star more massive than 18 M_{Sun} would leave behind a core with M > 2-3 M_{Sun} Neutron degeneracy pressure would fail and nothing can stop gravitational collapse

Core would collapse into a *singularity*, an object with Zero radius Infinite density

Black Holes

The ultimate extreme object

Gravity so strong not even light escapes

Infalling matter gets shredded by powerful tides & crushed into infinite density

 V_{esc} exceeds the speed of light.

According to General Relativity, there is no form of pressure that can stop its collapse to a singularity. $E=mc^2$ strikes again.

Black:

It neither emits nor reflects light

Hole:

Nothing entering can ever escape

Schwarzschild Radius

Light cannot escape from a Black Hole if it comes from a radius less than the *Schwarzschild Radius*:

$$R_s = \frac{2GM}{c^2}$$

M=Mass of the Black Hole For M=1 M_{Sun}, R_S~ 3km (if the entire mass of the Sun was squished to a ball with R~3km, it would be a black hole.)

Neutron Star vs. Black Hole

Neutron Star M=1.5 M_{Sun} R=10 km

Black Hole M=1.5 M_{Sun} R_S= 4.5 km R_{core}= infinitely small

The Event Horizon

 R_S defines the *Event Horizon* Events that happen inside R_S are invisible to the outside Universe Thugs that get inside R_S can never leave the black hole

The "Point of No Return" for a Black Hole

Gravity around Black Holes

Far away from a black hole:

Gravity is the same as for a star of the same mass

If the Sun were replace by a black hole with $M=1 M_{Sun}$, the planets would all orbit the same as before

Close to a black hole:

 $R < 3 R_S$, no stable orbits – all matter gets sucked in (not true for Newton's Law of Gravity)

At R=1.5 R_s, photons orbit in a circle!

Journey to a Black Hole: A Thought Experiment

Jack: in a spacesuit, is falling into a black hole, carrying a blue laser beacon Jill: orbiting the black hole in a starship at a safe distance in a stable circular orbit

Jack's point of view: sees the ship getting further away, flashes his blue laser once a second by his watch

Jill's point of view: Each flash takes longer to arrive (because it has farther to go), as is redder and fainter than the one before it.

Near the Event Horizon

Jack Sees:

His blue laser flash every second by his watch

The outside world look distorted as light is bent by the black hole

Jill Sees:

Jack's laser flashes come ~1 hour apart Flashes are redshifted to radio wavelengths Flashes are getting fainter with each flach

Down the hole

Jill Sees:

Sees one last laser flash after a long delay Flash is faint and at long radio wavelengths She never sees another flash from Jack....

Jack Sees:

Universe vanish as he crosses the Event horizon Gets shredded by strong tides near the singularity and crushed to infinite density

Jill's Conclusions:

The powerful gravity of a black hole warps space and time around it: Time appears to stand still at the event horizon as seen by a distant observer Time flows as it always does as seen by an infalling astronaut

Light emerging from near the black hole is *Gravitationally Redshifted* to longer (redder) wavelengths (not the same thing as the Doppler shift or Wien's Law).

Jack's Conclusions are considerably less coherent as he is shredded by the black hole.

Seeing what cannot be seen...

Q: If black holes are black, how can we see them?

A: By the effects of their gravity on their surroundings

A star orbiting around an unseen massive object

X-rays emitted by gas superheated as it falls into the black hole.

X-Ray Binaries

Bright, variable X-ray sources identified by X-ray observatory satellites (remember that X-rays cannot penetrate Earth's atmosphere, so these observations must be done from space).

Spectroscopic binary with only one set of spectral lines = the companion is invisible

Gas from the visible star is dumped on the companion, heats up as its gravitational energy is converted into heat, and emits X-rays

Estimate the mass of the unseen companion from the orbit

Black hole candidates will have $M > 4 M_{Sun}$

Black Hole Candidates

X-ray binaries with unseen companions of mass $>4~M_{Sun}$ too big for a Neutron Star

Candidates:

Cygnus X-1: M=6-10 M_{Sun} V404 Cygni: M > 6 M_{Sun} LMC X-3: M=7-10 M_{Sun}

None are as yet iron-clad cases

Work continues to refine our mass estimates

Example: Cygnus X-1

There is no sign of the companion at any wavelength (but X-rays emission high for a "normal" binary)

1) A red giant would be easily seen

2) A main sequence star would be seen with a little effort

3) Can't be a WD because $M > 1.4 M_{Sun}$

4) Can't be an neutron star because $M > 3 M_{Sun}$

Process of elimination says it's a black hole. Not as good a case as seeing the event horizon!

Black Holes are not totally Black!

"Classical" General Relativity says:

Black Holes are <u>totally</u> black

Can only grow in mass and size as more matter falls into them Last forever (nothing gets out once inside)

But:

General Relativity does NOT include the effects of Quantum Mechanics

Evaporating Black Holes

Black Holes evaporate very slowly by emitting Hawking Radiation

Vacuum fluctuations produce a particle–antiparticle pair near the event horizon, one particle falls into the hole, the other is radiated.

Very cold thermal radiation (T~10 nK)

Bigger black holes are colder (evaporate more slowly)

Takes a very long time...

5 M_{Sun} black hole takes 10^{73} years

10⁶³ times the present age of the Universe

Not important today, but could be important in the distant future as all other sources of radiation die off.