CHAPTER 13: NEUTRON STARS AND BLACK HOLES

NOTES AND SKETCHES

13.1: NEUTRON STARS

What Gets Left Behind

- Type I Supernova: Nothing left
- Type II Supernova (core collapse): Core not completely destroyed

Properties of a Neutron Star

- It's made of neutrons
- Very dense, very compact: Several solar masses squeezed into a ≈20km diameter ball
- Extremely high surface gravity (≈ 100 million times stronger than Earth's)
- Superfast rotation: Hundreds of rotations per second
- Extremely powerful magnetic field

13.2: Pulsars

- Detected in 1967 by a graduate student (Jocelyn Bell, Cambridge, UK)
- Object emits bursts of radio waves
- Each burst lasts the same length of time
- Bursts are recurring, spaced evenly in time
- Pattern is extremely stable

A Pulsar Model

- Repetition caused by rotation
- Rapidly rotating object (neutron star) emits beam from magnetic pole
- Magnetic pole and rotation axis not necessarily in the same alignment

Pulsars and Supernova Remnants

- Some supernova remnants have detectable pulsars at their center
- Pulsar wind: Magnetic field energizes/sends particles into the SN remnant, which "lights up" the remnant gas
- Doppler observations: High speeds (recoil from supernova explosion)

Neutron Stars and Pulsars

- All pulsars are neutron stars
- Not all neutron stars are pulsars
- As pulsar ages, rotation slows, pulses weaken (≈ tens of millions of years)
- Pulses may be emitted in a direction which is not visible from Earth (ok, so it's still a pulsar, we just can't tell)

How Many Are There?

- Tons and tons (pun intended)
- All high-mass ($\gtrsim 10\ M_\odot$) stars go supernova, most leave a neutron star behind
- Easier to detect a pulsar than a neutron star: estimate that for each known pulsar, probably several hundred thousand undetected neutron stars in this galaxy

13.3: NEUTRON STAR BINARIES

- Since most main sequence stars occur in binary (or more) pairs, no one should be surprised to find neutron stars with binary companions

X-Ray Sources

- This is almost the same mechanism as a classical (recurring) nova
- Neutron star accretes matter from its main sequence (or giant) companion
- When accreted mass exceeds Chandrasekhar limit, you get the same kind of sudden runaway hydrogen fusion on the surface of the neutron star as you would on a white dwarf
- Except it's not quite the same: it's more intense because of the greater density/gravity of the neutron star
- So you get a short, intense x-ray burst (instead of the classical novae visible helium flash)

Millisecond Pulsars

NOTES AND SKETCHES

- Fastest spinning pulsars (any faster and they would tear themselves apart)
- The faster the spin, the younger the pulsar (or so you would think, since they slow down as they age)
- These superfast spinners located in globular clusters (you know, the old folk's home for extremely old stars)
- These are probably not young pulsars, but old ones that have increased their rotation rates by accreting from companion stars
- About half of the observed ms pulsars have known binary companions
- And the rest? Well, a globular cluster is a crowded neighborhood. Very possible to have a passing or glancing encounter

Pulsar Planets

- At least one pulsar is known to have three planets orbiting
- Planets are not Earth-like, or planets which might have formed during solar system evolution
- Planets probably result from localized accretion after companion star destruction

13.4: GAMMA-RAY BURSTS

- First observed in the 1960s and 1970s by military satellites
- Compton GRO mapped bursts for about a decade
- Uniform distribution of events: no clusters
- Uniform rate of detection: Occur random, but about an event a day (again, no statistically significant clusters)

Distances and Luminosities

- Pretty tough to get a good measurement of distance
- Improved techniques since 1990s, more than 100 events accurately mapped
- Huge distances: events occurring billions of parsecs away
- Remember that distance = time: Billions of parsecs away means the event happened billions of years ago
- If we can still "see" it at these distances, it must be pretty darn bright: Hundreds of times brighter than a typical supernova

What Causes Bursts?

- They come from very small objects (millisecond pulses mean small object)
- Relativistic fireball: Jet of extremely hot gas, particles traveling at significant speeds (approaching c)

Merging Stars

- Binary system composed of two neutron stars (as opposed to a neutron star and a giant or main sequence companion)
- Pair spirals towards each other, eventually colliding/merging
- Outflow jets perpendicular to the plane of rotation (we have seen polar jets before: t-Tauri stars)

Hypernovae

- A super-deluxe super-complicated Type II supernova
- Would only happen with the most massive stars
- Rapid core collapse: Forms black hole before the supernova explosion, which "stalls" the process
- Black hole (massive gravity!) causes the remainder of the mass to form accretion disk, which gets sucked in
- Several things happen essentially simultaneously: Relativistic outflow jets, re-ignition of the supernova

Some of Both

- Both models are probably correct
- Merging neutron stars can explain the shorter observed bursts
- Hypernovae predictions match observations of longer duration bursts

13.5: BLACK HOLES

NOTES AND SKETCHES

The Final Stage of Stellar Evolution

- Less than ≈3M⊙: Neutrons are compressed to the point of literally touching
- Greater than ≈3M⊙: Gravity is so strong, it makes the neutrons get even closer than touching
- Gravity wins: F goes to infinity as distance goes to zero
- The gravity of a black hole is effectively infinite

Escape Speed

- Greater gravity means higher speed required to escape
- There is an upper limit to escape speed: c (speed of light)
- Even if gravity is not literally infinite, it can be large enough to prevent any mass or energy form escaping

The Event Horizon

- What combination of size and mass makes a black hole?
- Schwarzschild radius = radius at which escape speed becomes c
- Squeeze the Earth ($m = 6x10^{24}kg$) into a sphere with radius of 1 cm
- Squeeze 3M⊙ ($18x10^{30}kg$) into a sphere with radius of 9 km
- A 3M⊙ black hole is not actually a solid object with a 9 km radius; it's a singularity or a point
- Anything (matter or energy) that got closer than 9km would not be able to escape

13.6: EINSTEIN'S THEORY OF RELATIVITY

What Does This Have to Do With Astronomy?

- The whole semester has been about "reading" the information contained within electromagnetic radiation
- Relativity is going to explain an awful lot...things that Newton never dreamed of
- This is not the easiest topic we will discuss this semester

Michelson and Morley

- There was no really accurate way to measure the speed of light until the end of the 19th century
- These guys were OCD in the extreme (well, Michelson was, at least) and designed a very meticulous and precise method to measure c
- Precise enough that they should have been able to see the difference between light moving with the Earth or opposite the Earth's motion
- There was no difference
- Morley spent the rest of his life unsuccessfully trying to find the flaw in the experiment
- Michelson did not (there was no flaw in the experiment)

Special Relativity

- The speed of light measures exactly the same, no matter what your frame of reference
- All motion (displacement, velocity) is relative (that is, with respect to something). There is no fundamental fixed frame of reference.
- Space and time are co-dependent: Cannot separate them
- Notice that we call this a theory and not an hypothesis; it has been experimentally confirmed many times

Relativistic Mechanics

- At low velocities ($\ll c$), relativistic and classical (Newtonian) equations match (no conflict)
- At high velocities (approaching c), classical breaks down, relativistic mechanics takes over
- Time dilation: Time ticks more slowly for an object moving at relativistic speed
- Length contraction: As speed approaches c, the length of an object (measured in the direction of the velocity) approaches zero (squish)
- And if that was not fun enough, your mass also approaches infinity as your velocity approaches c

NOTES AND SKETCHES

General Relativity

- Changes our conceptions pretty dramatically
- How does gravity fit in with special relativity? Not very well or very easily.
- Start here, with the elevator thought experiment: In a closed elevator, could you tell the difference between gravity and acceleration? No, because they would feel exactly the same to you.
- Lots of math omitted: You can reproduce the effects of gravity if spacetime is curved

Tests of General Relativity

- Yes, this can be tested
- Classical gravity cannot predict or explain light bending
- General relativity predicts starlight will be bent massive objects (like the sun): This has been accurately measured since 1919
- Kepler's laws (classical gravity) cannot predict or explain slight precession in planetary orbits
- Mercury's orbit deviates exactly in accordance with general relativity's prediction

Curved Space and Black Holes

- You can't really explain black holes without relativity
- Black hole causes extreme curvature of spacetime--sort pinches off a bubble

13.7: SPACE TRAVEL NEAR BLACK HOLES

- Science fiction clichés aside, a black hole is not a voracious, ravening eater of galaxies

Tidal Forces

- Remember how the moon pulls on the earth: Closer side gets pulled harder, far side feels less force (hence ocean tides)
- Same idea: Difference in force between the closer side and farther side of an object being pulled by a black hole
- You do not have to be within the Schwarzschild radius to experience the tidal force
- Let's say you are in the process of getting sucked into a black hole (and fighting off space zombies, too. The probabilities are about the same)
- As your atoms are stretched into a very long, very thin filament, you will start to emit energy (high energy x-rays)
- Even though the black hole itself is not emitting either mass or energy, you will emit energy as your mass gets drawn in
- So a black hole could be detected by the energy emitted by the matter it consumes

Approaching the Event Horizon

- You can't really safely approach a black hole, so this is a job for a Giant Robot (ok, it does not have to be literally supersized, but it does have to be a robot)
- Set yourself up in orbit at a safe distance, then send your Giant Robot spiraling towards the event horizon
- Program Giant Robot to send you signals of known frequency at a known interval (like a pulse of 450THz red light every second)

Gravitational Red Shift

- If you are expecting to receive a 450THz signal every second, you are in for a surprise
- The frequency of the pulse starts to decrease as the probe approaches the event horizon
- The spacing of the pulses also starts to increase: Longer time in between subsequent pulses
- The photon emitted by the probe needs energy to escape the gravity of the black hole: $E = hf$, so if E decreases, so does f (h = constant)
- The amount of redshifting increases as Giant Robot gets closer to the event horizon

Time Dilation

- This gets a little philosophical, but: How do you know that time is actually passing? Seriously, how do you know that it is later now than it was an hour ago?
- Something has to change for you to perceive the passage of time (think about how movie clichés show you time passing)
- So, as the pulses from the Giant Robot get increasingly red-shifted to lower and lower frequency, you receive them less frequently
- Eventually, as the probe gets to the event horizon, you see it as "frozen" in time (because the frequency has dropped to zero)
- Giant Robot, however, does not notice anything unusual, and continues, from its perspective, to emit the same 450THz signal every second

Tidal Forces, Again

- The tidal force (remember: differential force!) at the event horizon is greater for a small black hole than a huge one
- A really, really huge (millions of M) black hole would create tidal forces that were technically survivable
- The problem is that once you're in, you're in: there's no way back out again
- Surviving the event horizon is a purely Pyrrhic victory; you are still going to be crushed into an infinitely small point particle

Deep Down Inside

- Nobody knows. Shrug. Nobody *can* know—not right now
- Newtonian gravity is useless here; general relativity is incomplete
- When quantum mechanics is combined with general relativity (Nobel Prize for you, if you can do it), then we may be able to create a framework within which we can understand what's going on in there
- In the meantime, we can have lots of fun and write lots of scifi books and movies using black holes as gateways to time travel, alternate universes, and intergalactic dominions

3.8: Observational Evidence for Black Holes

Black Holes in Binary Systems

- Remember: More massive the star, the shorter the lifespan
- Perfectly reasonable for a binary system to consist of two supergiant stars
- Whichever one is more massive will evolve faster, and could become a black hole while its companion was still on the main sequence

Cygnus X-1

- Remember that you only have to watch one star to deduce that it has a binary companion (even if you can't see it, its gravity gives it away)
- Cygnus X-1: The binary companion of a 25M blue (main sequence) supergiant
- By watching the blue giant, you can determine the period (and the mass of Cyg X-1, which is about 10M)
- You can't see the black hole, but as it accretes mass from its companion, you can see the x-rays emitted by the infalling matter
- Size limit is about 300 km diameter

Black Holes in Galaxies

- Many galaxies (ours, too) have very, very massive black holes at their centers
- Again, no direct observation of the hole itself, you always have to observe it by the effect is has on the surrounding matter
- Also possible that medium-large black holes exist at the centers of large globular clusters

Do Black Holes Exist?

- Yes. Yes, they do.