Astronomy 162, Week 7
General Relativity

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Neutron Stars and Gravity

- We have considered the extreme physical conditions produced within neutron star by the collapse of the core
- Now consider the effect of the gravity itself
  - Gravitational pull at surface of neutron star is incredibly strong
  - It affects significantly the radiation emerging from the surface

General Relativity

- Strong gravity means we must consider general relativity
- This will lead us to the concept of black holes

Review of Special Relativity

- Recall Einstein and special relativity
- Speed of light is same for all (inertial) observers
  - That led to time dilation and length contraction
  - Also to $E = mc^2$
- Refer to Ch. 24-1

General Relativity: Principle of equivalence

- Another brilliant insight of Einstein
- Has three parts:
  - equivalence of inertial and gravitational mass (Galileo's principle)
  - laws of physics same in freely falling lab as in lab at rest far from any mass
  - physical laws in accelerating lab same as in stationary lab in gravitational field

Fig. 24-3, The Equivalence Principle

- First two seem obvious (now)
- Galileo dropped two different kinds of balls
  - both fell to the ground at the same time
- Astronauts in space don’t feel gravity
  - they are freely orbiting (falling) in a gravitational field

- All three points bring new consequence:
  - Light must also be subject to gravity
  - Otherwise, astronaut could tell if he/she was in accelerating space ship or subject to gravity on earth

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Black Holes

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Light and Gravity

- Consequence of General Relativity
- Light will be deflected (bent) by a gravitational field
- Light will have a redshift in a gravitational field (see Ch. 24-2)

Concept of Spacetime

- Light has finite speed
- No signal can travel faster than light
- We see sun as it was 8 minutes ago
  - some events can be outside our horizon
  - for example, we don’t know what the sun is doing at this instant

Heart of General Relativity

- Matter in universe affects (curves) spacetime
- Light follows geodesics (shortest paths)
- Path of light curved according to geometry of spacetime
  - Einstein worked to establish a geometric basis for physics and the effect of gravitation

Fig. 24-4, Gravitational Curvature of Spacetime

Tests of General Relativity

- Deflection of starlight near sun (Fig. 24-5)
  - Observed in famous eclipse of 1919
  - Confirmation made Einstein famous
- Change in orbit of Mercury
- Gravitational redshift
  - observed on earth in a brilliant experiment
  - observed on sun and in white dwarfs in binary systems

Fig. 24-5, Gravitational Deflection of Light
Fig. 24-6, Precession of Mercury's Orbit
Fig. 24-7, Gravitational Redshift

- Now - also checked using time delay of light in a distant space probe
- So far - general relativity is confirmed

Gravitational waves and binary pulsar

- Gravitational field of moving object changes with time
- Fast moving, massive object can produce notable effect
- Discovery of binary pulsar (1979) with period of 8 hrs gave another key test of general relativity

Why?

- Orbital velocity high enough (0.1 c)
- Pulsar such a good clock - changes in orbit detectable
- Long-term observations of pulsar have now confirmed G.R. to high degree of accuracy
- Hulse and Taylor received Nobel prize for this work

- U.S. now has project to detect gravitational waves directly
  - LIGO
- Need to detect changes in separation of 1 part in 10^{20}!
- Should be able to detect gravitational waves from a supernova in our galaxy

Black Holes

- Suppose gravitational field of an object is so strong
  - escape speed is speed of light
  - then light would not be able to escape
- We would have a black hole

- Imagine what happens as we keep shrinking a star
  - For a neutron star - light passing by is bent by about 30 deg.
  - Keep shrinking the star - soon light will travel in a circular orbit - photon sphere
  - Eventually light will not be able to escape surface (Fig. 24-8)

Fig. 24-8, Light around a forming black hole

Schwarzschild radius

- Schwarzschild was first to calculate radius at which light could not escape
- Smaller objects are black holes!
  - Schwarzschild radius for 1 solar mass is 3 km (neutron star radius is about 10 km, not much bigger than a black hole)
  - Radius is proportional to mass
  - For 10 solar masses, radius is 30 km

Limits on Masses of Neutron Stars

- Neutron stars that weigh more than about 3 solar masses cannot support themselves against gravity
- They collapse to become black holes
- (This is analogous to Chandrasekhar limit for white dwarfs)

How to make a black hole?

- From stars - probably from supernova in very massive star
- How to observe a black hole?
  - Through its gravitational field
  - (Still the same outside the hole)
  - Also, matter gets very hot falling towards the black hole
  - Emits X-rays

How to detect a black hole?

- If light cannot escape, how can we find a black hole?
- Through its gravitational attraction
- And through emission from the hot gas falling towards it
- Thus, binary X-ray sources are candidates for black holes
- See Figs. 24-10 and 24-11

Fig. 24-10, Companion star to Cyg X-1

Fig. 24-11, The Star, Accretion Disk, and Black Hole

Falling into a black hole

- What happens as you approach a black hole?
  - Besides getting fried by the heat, blasted by the radiation, and torn apart by the tidal forces,
    it would be interesting
- Two parts to the question
  - What is seen by outside observer?
  - What is sensed by you?

- Because of relativistic effects,
  outside observer sees time slowing down for you
  - gravitational redshift becomes greater and greater
  - to outside observer, you never quite reach the event horizon (Schwarzschild radius)

- You, however, don’t see anything so unusual
  - you pass right through the event horizon (but can never get out again or send a signal out)
  - in principle, continue right through to center
  - the singularity
  - can only speculate on what happens inside the black hole

Fig. 24-18, Falling into a Black Hole

Fig. 24-9, Curved Spacetime around a Black Hole

Other origins of black holes

- Have seen how a supernova may produce a black hole
- Very massive black holes may occur in centers of galaxies (discuss later in course)
- Massive star clusters may collapse
- Intriguing possibility
  - formation of mini-black holes in big bang

Fig. 24-15, Structure of a non-rotating Black Hole

- See the book “Black Holes and Time Warps”
- by Kip Thorne

Fig. 24-15, A Rotating Black Hole

Properties of A Black Hole

- A black hole is characterized by 3 parameters:
  - Mass
  - Charge
  - Rotation (angular momentum)

Evaporation of black holes

- Stephen Hawking (Brief History of Time)
  - speculated on what happens near a black hole
  - realized there is a chance of particle creation from fluctuations in energy density
  - normally particles would annihilate
  - but, near a black hole, one particle might be captured
  - other particle escapes

Fig. 24-17, Evaporation of a Black Hole

- the black hole slowly evaporates
- this can only occur (within lifetime of universe) for mini-black holes
- they might disappear in burst of gamma rays
- (enjoy the book - impress your friends)

Astronomy 162, Week 7
The Galaxy

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The galaxy

- We will consider first
  - the basic structure and geography of the galaxy
  - the location of the center of the galaxy
  - spiral structure

Milky Way Galaxy

- Galaxy - derived from the Greek, meaning milky
  - Milky Way - Via Lactae
  - Galileo - 1610 - showed it was composed of stars (by looking through his telescope)
  - Still one of most majestic sights in (a dark) sky especially in the southern hemisphere
  - Look for Sagittarius, Scorpius this summer

Parts list

- We have learned about
  - stars, how they form, evolve, die
  - nebulae
  - interstellar gas (mostly hydrogen, helium)
  - interstellar dust
  - molecular clouds and regions of star formation

- Now we will start fitting everything together
  - the above parts are the building blocks of galaxies
  - galaxies, in turn, are the building blocks of the visible universe

Geography of Milky Way

- Our Milky Way :
  - disk
    halo
    spiral arms
  - diameter is about 30,000 parsecs
  - thickness is about 300 parsecs
  - our sun is about 8000 parsecs from center
  - has spheroidal nuclear bulge of stars near center

Herschel (1738-1822)

- Made first attempt to determine nature of Milky Way (Fig. 25-2)
  - developed method of star gauging (counting)
  - he believed we were at center of galaxy
  - but he was wrong - dust blocks our view of the true center of the galaxy
  - still, his technique was valid (and is basis of modern approach)

Shapley

- At beginning of 20th century, scale of Milky Way and universe was not known
- Harlow Shapley provided first leap in understanding in 1917
  - used globular clusters

Use of globular clusters

- Recall globular clusters are large, bright, can be seen to great distances
  - many are distributed away from galactic plane
  - thus, they avoid the obscuring dust

Distances to Globular Clusters

- Shapley used cluster variables (RR Lyrae stars) to find distances to nearer clusters
- Then he estimated distances to others from their sizes
- He mapped their distribution in space

Fig. 25-5, RR Lyr Variables in Globular Cluster

Distribution of Globular Clusters

- Shapley realized globular clusters were not centered on the sun
- He made the bold assumption that they were centered on the galaxy
  - thus showed that the sun is distant from center of galaxy
  - was first to establish the size and scale of the Milky Way

Fig. 25-3

Fig. 25-7, The Milky Way

Stellar Populations

- Establish connection between
  - Basic components of Milky Way
    - Disk, with spiral arms
    - Halo
    - Nuclear bulge
- and their underlying properties
  - age, location, type of orbit in Milky Way, and composition

Disk of Milky Way

- Start with observed properties
  - location - bright band of Milky Way indicates that most stars in our neighborhood are in disk
  - velocities
  - most stars in neighborhood of sun travel with it
  - they have low velocities relative to sun
  - they are disk stars

Halo

- Some stars have high relative velocities
  - rotate more slowly about center of galaxy
  - often travel above/below disk
  - they are halo stars

Populations I and II

- Age, location, type of orbit, and chemical composition are often (but not always) correlated
- Walter Baade - Mt. Wilson - W.W. II
  - noted two populations of stars
    Pop. I - blue stars in spiral arms
    Pop. II - red stars in bulge, halo, globular clusters

- What are some of the differences between the two?
  - age, composition, orbit, location
- Baade's work was important conceptual advance
  - preceded knowledge of stellar and galactic evolution
  - helped shape understanding of both

In reality

- The true situation is more complicated
  - still useful to think of Pop. I as a young, disk population
  - Pop. II as old, halo population
  - but, bulge can be old, rich in heavy elements
  - Small Magellanic Cloud is young but poor in heavy elements
  - Evolution was not uniform everywhere

Summary

- Population I
  - Young stars, clusters, emission nebulae; located in disk of galaxy, usually near spiral arms; have chemical composition like sun (metal rich)
- Population II
  - Old stars, globular clusters, little gas/dust; more evolved, lower abundance of heavy elements (metal poor); located in halo of galaxy; have different orbits in Milky Way

Galactic Disk

- Figs. 25-7, 25-8 show the disk in edge on view and the halo of the galaxy
- Both the observed motions of stars and considerations of gravity show the disk must be rotating about the center of the galaxy

Fig. 25-6, The Infrared Milky Way

Fig. 25-7, Schematic View of Milky Way

Rotation of Galaxy

- Sun is in orbit around center of galaxy
  – Moving at about 220 km/s
  – Distance is about 8000 pc from center
  – Takes about 225 million yrs to complete one orbit
  – Note rotation curve (Fig. 25-16)
  – From Kepler's law, can estimate mass of galaxy to be about 2×10^{11} solar masses