Planet Formation - Summary

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This summary is based on the book Chapter 17 from Carroll, Bradley W., and Dale A. Ostlie. An Introduction to Modern Astrophysics

1 General Relativity (GR)

Observational evidence of curved spacetime and GR:

- apparent positions of stars change during a Solar eclipse
- gravitational lensing, e.g. Einstain rings, Einstein crosses
- the perihelion precession of Mercury
- spacetime near Earth is only slightly curved, but the curvature is great enough to produce the circular orbits of satellites.
- gravitational redshift (not the same as the Doppler redshift)

In GR the effect of **mass and energy** on spacetime is producing curvature. Gravity is the result of objects moving through curved spacetime, and everything that passes through, even massless particles such as photons, is affected. Effects of the curved spacetime are: Time runs more slowly in curved spacetime.

The Principle of Equivalence: All local, freely falling, nonrotating reference frames are fully equivalent for the performance of all physical experiments. $\rightarrow$ local inertial reference frames.

Time passes more slowly as the surrounding spacetime becomes more curved, an effect called **gravitational time dilation**. The **gravitational redshift** is a consequence of time running at a slower rate near a massive object.

Einstein's field equations for calculating the geometry of spacetime produced by a given distribution of mass and energy.

Spacetime diagrams (Minkowski diagrams):

- The path followed by an object as it moves through spacetime is called its **worldline**.
- A light cone is: the straight worldlines of light rays make $45°$ angles with the time axis.
- Light cones act as spacetime horizons, separating the knowable from the unknowable.
- spacetime interval: distances on a space time diagram
- time like regions / intervals
- space like regions / intervals
- light like intervals
- Lorentz transformation
- proper time: The interval measured along any timelike worldline divided by the speed of light is always the proper time measured by a watch moving along that worldline.
- proper distance
- differential distance formula called a **metric**
- flat spacetime metric
- curved spacetime metric - Schwarzschild metric
- The paths followed by freely falling objects through spacetime are **geodesics.**
- **coordinate speed** is the rate at which its spatial coordinates change.

2 Black Holes

Gravitational collapse of a massive star that had exhausted its sources of nuclear fusion. The theoretical mass limit for a neutron star is approximately 3 $M_\odot$. Compact objects more massive than 3 $M_\odot$ are considered to be black holes. For a non rotating black hole we can calculate the **Schwrazschield radius**, using the Schwarzschield metric. A star that has collapsed down within the Schwarzschild radius is called a black hole. The **event horizon** is the spherical surface at the Schwarzschield radius.

At the center of a black hole is the **singularity**, a point of zero volume and infinite density where all of the black hole's mass is located. Spacetime is infinitely curved at the singularity. Cloaking the central singularity is the event horizon. This is also called the "Law of Cosmic Censorship" which states that a singularity can never be observed.

Types of black holes depending on the mass:

- stellar mass black holes (3 - 15 $M_\odot$) - corecollapse of a sufficiently massive supergiant star, neutron star in a close binary system, $\rightarrow$ X-ray binaries
- intermediate mass black holes (100 - 1000 $M_\odot$) $\rightarrow$ ultraluminous X-ray sources, correlation with the cores of globular clusters $\rightarrow$ possibly a result of stellar mergers
- supermassive black holes ($10^5 - 10^9$ $M_\odot$) $\rightarrow$ in the centres of most galaxies, closely linked with some bulk properties of galaxies, implying an important connection between galaxy formation and the formation of SMBHs. $\rightarrow$ the source of AGN activity, the Schwarzshield radius is comparable in size to the Solar System

Primordial black holes: are hypothetical black holes that formed soon after the Big Bang. In the inflationary era and early radiation-dominated universe, extremely dense pockets of subatomic matter may have been tightly packed to the point of gravitational collapse, creating primordial black holes without the supernova compression needed to make black holes today. Because the creation of primordial black holes would pre-date the first stars, they are not limited to the narrow mass range of stellar black holes.

X-ray binary sources: can be neutron stars or stellar mass black holes accreting matter from inflated binary companions. $\rightarrow$ mass transfer $\rightarrow$ loss of gravitational energy $\rightarrow$ radiation in X-rays.

Rotating black holes: Kerr metric, event horizon has assumed the shape of an ellipsoid. The BH induces a rotation in the surrounding spacetime, a phenomenon known as **frame dragging**. A nonspherical region outside the event horizon called the **ergosphere** where any particle must move in the same direction that the black hole rotates.

Any black hole can be completely described by just three numbers: its mass, angular momentum, and electric charge. For astrophysical BHs the angular momentum is considered to be non zero and the charge is considered to be 0.

The Penrose process: energy is taken from the rotation of the black hole. In the process, a body falls into the ergosphere. At its lowest point the body fires a propellant backwards; however, to a faraway observer both seem to continue to move forward due to frame-dragging. The propellant, being slowed, falls to the event horizon of the black hole. The remains of the body, being sped up, fly away with an excess of energy.

The **Blandford-Znajek process** is a mechanism for the extraction of energy from a rotating black hole. This mechanism is the most preferred description of how astrophysical jets are formed around spinning supermassive black holes. The magnetic field generated by the accretion disk extracts spin energy.

Measuring the **spin of a black hole:** Based on the width of the iron lines emitted by the accretion disk of the BH.

Wormhole: a hypothetical tunnel between two points in spacetime separated by an arbitrarily great distance. There is no known mechanism that would allow a wormhole to arise naturally

Hawking radiation: pair production just outside the event horizon of a black hole. Ordinarily the particles quickly recombine and disappear, but if one of the particles falls into the event horizon while its partner escapes than we get Hawking radiation. $\rightarrow$ theoretically black holes can slowly evaporate trough Hawking radiation, however, so far there is no evidence for this.

The **information paradox** appears when a BH evaporates away entirely through Hawking radiation. Hawking's calculation suggests that the final state of radiation would retain information only about the total mass, electric charge and angular momentum of the initial state. Since many different states can have the same mass, charge and angular momentum, this suggests that many initial physical states could evolve into the same final state.

A sonic black hole, dumb holes or acoustic black hole, is a phenomenon in which phonons (sound perturbations) are unable to escape from a region of a fluid that is flowing more quickly than the local speed of sound. $\rightarrow$ evidence for the sonic version of Hawking radiation