Khatra Adibasi Mahavidyalaya: Lecture Notes

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Earth and the Universe

The Universe & its origin

Cosmology is the branch of science concerned with the structure and evolution of the Universe on the largest scales of space & time. Gravity governs the structure of the universe on these scales and determines its evolution. Three basic **observational facts** about the Universe on the largest distance scales are:

- The Universe consists of stars & gas in gravitationally bound collections of matter called galaxies, along with diffuse radiation, dark matter of unknown character & dark energy.
- The Universe is expanding.
- Averaged over large distance scales, the Universe is *homogeneous* (the same in one place as in any other) & *isotropic* (the same in one direction as in any other). The densities of galaxies, radiation, dark matter & dark energy are uniform.

Cosmogony is the study of the *origin* of any particular astrophysical system, e.g. cosmogony of the Universe, the Solar System, the Earth-Moon System etc. The Big Bang cosmological model is the currently accepted theory in the cosmogony of the Universe. Spectra of starlight from nearby galaxies show Doppler shift, which indicate that they are moving away from us with a velocity V satisfying

$$V = H_0 d,\ \ H_0 = 72 \pm (7\, km/s)/Mpc, \tag{1}$$

d being the distance to the galaxy & H_0 is Hubble's constant. A par-sec (pc) is a standard distance unit in cosmology, $1\,\text{pc} = 3.26\,\text{light-years}$ & $1\,\text{Mpc} = 10^6\,\text{pc} = 3.09 \times 10^{22}\,\text{m}$. This is called **Hubble's Law** & every galaxy sees its nearby galaxies receding according to the above law (see Fig.1). This motion is apparent & is due to the homogenous & isotropic expansion of the Universe, (*i.e* there is no center of expansion & about every galaxy the expansion is direction-independent). By expansion of the Universe, it is meant the entire $4-d$ space-time is expanding. Hubble's law is valid only at inter-galactic distances $\sim 10Mpc$ where the recesssion due to expansion dominates any other velocity acquired due to gravitational attraction of local objects.

Rewriting Eq.1 as $d = Vt_H$, with $t_H = 1/H_0 \sim 14\,\textbf{Ga}$(1Ga= 10^9 years), we extrapolate in the past to an instant of time when the ditances between galaxies goes to zero. This is the **Big Bang** —a time of infinite density, infinite temperature & infinite spacetime curvature, *i.e.* a moment where all physical quantities have a **singularity** . Near this early time matter & radiation had not yet condensed into galaxies but existed in thermal equilibrium with each other as a smooth, hot fluid. More precise observations show the age of the Universe as $13.77\,\text{Ga}$.

As the universe expanded, both matter and radiation cooled while remaining in thermal equilibrium. Radiation at thermal equilibrium is black-body radiation which is necessarily homogeneous & isotropic & has the same temperature as the matter which absorbs & emits it. At a time $\sim 4 \times 10^5$ yrs earlier than the present era (about 370,000 years after the Big Bang), the temperature dropped enough such that the photon energies were less than binding energies of electrons in atoms. As a result, previously free electrons combined with nuclei to make neutral, transparent matter— mostly hydrogen and helium atoms. Light emitted at that time when the temperature was approximately 3000 K (with a peak wavelength in the IR region,*i.e.,* $\lambda_m = 960\,\text{nm}$, given by Wien's Law: $\lambda_m T = 2.898 \times 10^{-3}\,\text{m.K}$) has been traveling to us ever since and forms the **cosmic microwave background radiation** (CMBR). This time is called the *Recombination* epoch, when the photon energy was $\sim 1.2\,\text{eV}$ ($= hc/\lambda_m$).The intervening expansion has cooled the radiation to a temperature of $2.73\,\text{K}$, whose peak wavelength $\lambda_m = 1.1\,\text{mm}$ is in the microwave range. A map of the temperature of this radiation on the sky is as close as we can come to a picture of the universe at the big bang. This map shows remarkable isotropy apart from tiny fluctuations $\sim 10^{-5}$ K. The fluctuations away from exact isotropy are important, however, because they are signatures of density fluctuations that in the intervening time grew by gravitational attraction to become the galaxies we see today.

Galaxies

The visible matter in the universe is mostly contained in galaxies—gravitationally bound collections of stars, gas, and dust. A typical galaxy has about 10^{11} stars & a total mass of about $10^{12}\, M_\odot$. Galaxies are of three broad types-

- *Elliptical* galaxies: 60% of all galaxies. The stars revolve round the galactic center along a preferred plane, resulting in an ellipsoidal shape. They contain little inter-stellar gas, which means star formation is less, the stars are all old.

- *Spiral* galaxies: (30%), which have spiral arms (see Fig.2) & are rich in inter-stellar gas. Hence they are sites of star formation.

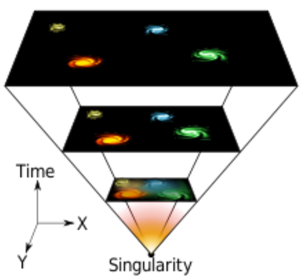

Figure 1: Galaxies recede from each other due to expansion of the space in between.

- *Irregular* galaxies: (10%)

Our galaxy, the **Milky Way**, is a spiral galaxy with a visible diameter of $(1-2)\times 10^5$ light-years. It is estimated to contain $(1-4)\times 10^{11}$ stars & at least that number of planets. It rotates clockwise, as seen from north. The rotation is not uniform, increases radially from the center for a distance before becoming constant. The Sun, about 25000 light-years from the center, rotates arond the center at 225 km/s, completing one turn in 2×10^8 years.

The view from Earth, an off-center point (see Fig.3), is of the central region of the galactic plane where stars are too densely clustered to be individually distinguished by the naked eye. This region appears as a hazy white band across the sky (see Fig.4), from which the galaxy derives its name. In night sky observing, although all the individual *naked-eye* stars in the entire sky are part of the Milky Way Galaxy, the term "Milky Way" is limited to this band of light representing the central bulge.

Asteroids & Meteorites

Asteroids are minor planetary bodies that orbit the Sun between Mars & Jupiter in prograde motion. They were not able to assemble into a single body because of Jupiter's perturbations. During their orbital motions, they frequently collide with each other and continually fragment into smaller and smaller pieces. An asteroid/comet 10 km wide struck the Earth 66 million years ago & led to the formation of a crater 180 km across & 100 km deep in today's Mexico. As a consequence of the impact an equivalent amount of rock material was instantaneously vaporised & a dark cloud of dust & smoke enveloped the Earth for several weeks. This caused the extinction of about three-fourths of all plants & animal species, including the dinosaurs.

Meteorites The smaller asteroids are so numerous & their collisions so frequent, that even smaller fragments are continually produced. These are called *meteoroids*. Some meteoroids are perturbed (probably by passage of comets) & thrown into orbits that bring them close to the Earth when they are captured. These are called meteorites. On average, 550 meteorites fall on Earth each year. The masses of meteorites vary over a large range. The largest meteorite discovered weighing 60 tons was found in Namibia.
Meteorites are classified into three major groups:

Figure 2: UGC 12158 is a spiral galaxy 118 Mpc distant

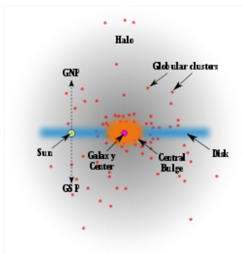

Figure 3: Schematic profile of Milky Way

Figure 4: Panoramic view of Milky Way at night from Chile

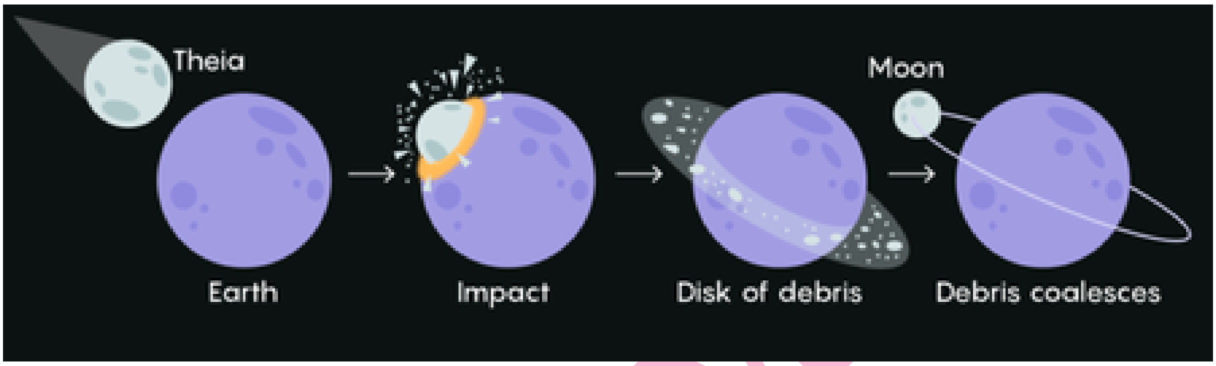

Figure 5: The Giant Impact hypothesis for the Moon's origin

(i) *stony* meteorites (or *aerolites*): 92.8% of population, consisting of silicate minerals with little metal.

(ii) *stony-iron* meteorites (or *siderolites*): 1.5%, consist of mixtures of silicates & metals

(iii) *iron* meteorites (or *siderites*): 5.7%, consists primarily of metal (Fe-Ni alloy).

The Moon

At least 61 *satellites* orbit the planets. The Moon is our only satellite whose mass is 1.23% of the Earth. It is the largest satellite w.r.t its planet. It is at a mean distance of $384,401\,\mathrm{km}$,i.e., 1.282 light-seconds. The mean density of the Moon- $3.3\,\mathrm{g/cm^3}$ is less than Earth's ($5.52\,\mathrm{g/cm^3}$). Trapped gases released during its formation escaped into space (gravitational field 16% that of the Earth). The resulting lack of atmosphere means its surface still has the craters formed due to impact by planetesimals.

The Moon's **origin** is explained by a Mars-sized body striking the Earth making a ring of debris that coalesced into a single body as shown schematically in Fig 5. This is called the **Giant-Impact hypothesis** & is the currently scientifically favoured hypothesis for Moon's formation. The hypothetical colliding object is called *Theia*.

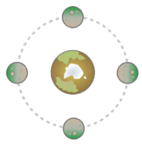

Figure 6: The satellite's green area is never seen due to synchronous rotation.

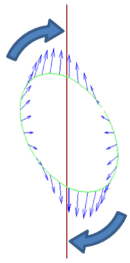

Figure 7: The planet is in the downward direction along the red line.

Synchronous Rotation of the Moon: The Moon's orbital & rotational periods are equal, hence the same hemisphere of the Moon (Fig. 6) is seen from Earth througout its orbital period of 27.3 days. This is an example of **tidal locking**, the Moon being 1 : 1 locked with the Earth.

The mechanism of tidal locking is explained by *tidal forces* acting on the Moon due to the *differential* gravitational field of the Earth on the surface of the Moon. As the gravitational field is inversely proportional to the square of the distance, it is stronger on the side facing Earth and weaker on the opposite side. The tidal force is due to this difference & is proportional to the Earth's mass (the body causing the force) and the Moon's radius(the body on which the force acts). Since Earth has 81 times more mass than the Moon but only 4 times its radius, Earth produces around 20 times stonger tidal force on the Moon, than the tidal force of the Moon on Earth.

This results in a distortion of the spherical shape of the Moon, leading to an elongation along the axis orientated towards Earth and a compression along directions perpendicular to this axis. These distortions are called *tidal bulges*. If the tidal bulges are misaligned with the line towards the Earth at any point on the Moon's orbit, the tidal forces exert a torque that tends to rotate the body into alignment. If Moon's rotational period is shorter than its orbital period, the bulges lead the line towards Earth in the direction of orbital motion. If the rotational period is longer, the bulges lag behind this line as is shown in Fig.7 where the deformed satellite is depicted as a green *prolate ellipsoid*. In both cases, the tidal torque tends to rotate it to alignment, which is the alignment for synchronous rotation.

Spin & Orbit of the Earth

The **celestial sphere** is an imagined sphere of infinite radius centered on the Earth where all astronomical objects whatever be their distance appear to be embedded and execute apparent motion due to the rotation and revolution of the Earth. In short, it is the sky. This apparent motion is called **parallax** and the parallax angle of an object for two lines of sights is the angle between those two lines. Nearby objects show a *larger* parallax compared to distant objects. This also implies two nearby objects at different distances will exibit larger *relative* motion than two faraway objects at different distances. The **fixed stars** compose the background of astronomical objects (*i.e.* distant stars, see Fig 8) which have negligible *relative* motion compared to nearer Solar system objects.

The trajectory of the Sun w.r.t Earth in the celestial sphere is called the **ecliptic**. (It is also the orbit of the Earth in a heliocentric reference frame). The projection of Earth's equator on the celestial sphere is the *celestial* equator.

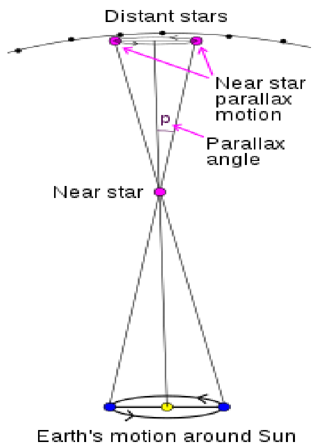

Figure 8: The parallax of a nearby object against a background of fixed stars.

Cosmic Rays

Cosmic rays are high-energy protons and atomic nuclei that move through space at nearly the speed of light. They originate from the sun, from outside of the solar system in our own galaxy, and from distant galaxies. Upon impact with Earth's atmosphere, cosmic rays produce showers of secondary particles, some of which reach the surface; although the bulk is intercepted by the magentosphere or the heliosphere. Of primary cosmic rays, which originate from astrophysical processes outside of Earth's atmosphere, about 99% are the bare nuclei of well-known atoms (stripped of their electron shells), and about 1% are solitary electrons (that is, one type of beta particle). Of the nuclei, about 90% are simple protons (i.e., hydrogen nuclei); 9% are alpha particles, identical to helium nuclei; and 1% are the nuclei of heavier elements, called HZE ions. A wide variety of potential sources for primary cosmic rays have been found, including supernovae, active galactic nuclei, quasars, and gamma-ray bursts. These rays mostly originate from outside the Solar System and sometimes even the Milky Way. When they interact with Earth's atmosphere, they are converted to secondary particles. Secondary cosmic rays, caused by a decay of primary cosmic rays as they impact an atmospheric molecule like nitrogen or oxygen (see Fig.9, include photons, leptons, and hadrons, such as electrons, positrons, muons, and pions.

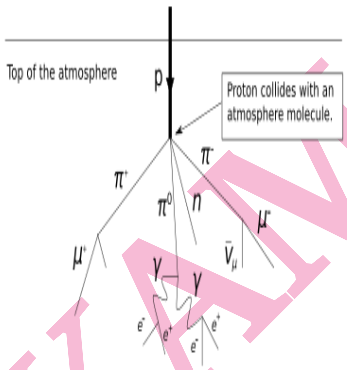

Figure 9: Primary cosmic particle collides with a molecule of atmosphere, creating an air shower.