Case Study Round 1

ORIGIN AND EVOLUTION OF THE UNIVERSE

Overview :

The natural tendency of a civilization is to expand upon its knowledge once new inconsistencies are discovered. The Universe was believed to have been static and homogenous on an average scale for a long time. And this caused problems. For instance, a homogenous and static universe would lead to a paradox of infinite Suns (Olber's Paradox). This paradox is resolved once we consider a dynamic model for the Universe.

In 1929, Edwin Hubble gave what is called Hubble's Law in his honor: a property that implies that the Universe is expanding. This marked the beginning of evidence for a new dynamic model of the Universe, one for which the laws of modern physics were worked backward in time to predict what might have happened at the Universe's beginning while being consistent with this expansion theory. That is, if the laws as we know them are themselves valid at that point at all. As is the property of any scientific theory, while an excellent candidate for the true nature of reality, this Universe model still falls short of explaining certain fundamental phenomena.

General Instructions

This is the Round 1 Problem Statement of the Case Study. It contains 4 Questions based on the origin and evolution of the universe, and each question has a specific weightage, as mentioned along with the questions. Some of the sub-questions of question 3 are based on datasets found along with the questions. You are advised to refer to the dataset only for these questions.

Questions

Q1. The Big Bang theory explains how the cosmos expanded from a highly dense and hot starting condition. It is the most popular cosmological theory that explains how the world evolved from the earliest known periods to its final large-scale shape. The model also thoroughly explains a wide range of observable phenomena, such as the quantity of light elements, the cosmic microwave background (CMB) radiation, and large-scale structure. **(6 Marks)**

A. Which theory predicts the production of nuclei other than those of the lightest isotope of Hydrogen during the Big Bang? How do modern-day observation and this theory provide evidence in favor of the Big Bang Theory?

B. Why is it hard to predict any events in the first 10^{-32} seconds of the Big Bang? What inconsistency did the simplistic expansion by general relativity pose, and what other theory was adapted for explaining the expansion just after the Big Bang?

Q2. Cosmic Microwave Background Radiation (CMB) is landmark evidence of the Big Bang origin of the universe. When the universe was young, before the formation of stars and planets, it was denser, hotter, and filled with an opaque fog of hydrogen plasma. As the universe expanded, the plasma grew cooler, and the radiation filling it extended to longer wavelengths. When the temperature had dropped enough, protons and electrons combined to form neutral hydrogen atoms. Unlike the plasma, these newly conceived atoms could not scatter the thermal radiation by Thomson scattering, so the universe became transparent. Cosmologists refer to the period when neutral atoms first formed as the *recombination epoch*, and the event shortly afterward when photons started to travel freely through space is referred to as photon decoupling. **(9 Marks)**

A. What incident led to the discovery of Cosmic Microwave Background Radiation? How was it confirmed that the source of this radiation was due to the beginning of the recombination epoch?

B. A photon could travel an average distance before the moment of recombination (also called the mean free path). Only considering the interaction of free electrons with photons, calculate the mean distance.(Thomson scattering cross section = $6.65 * 10^{-29} m^2$, density of electrons = 200 million electrons per cubic meter).

C. How can we measure the curvature of space? How does the Cosmic Microwave Background radiation help us predict our universe's curvature?

D. Why are there minute thermal discrepancies in the Cosmic Microwave Background Radiation, and How did it lead to the formation of Galactic clusters?

Q3. String theory predicts that the universe is like a bubble expanding and dying. Assuming this hypothetical bubble universe is similar to a spherical soap bubble and given some surface tension(T), some expansion force (dark energy), and some retracting forces (gravity, dark matter). **(15 Marks)**

Repulsive Pressure(N/m^2)=k_1/r^3 where k_1 is positive constant

Attractive Pressure(N/m^2)=k_2/r^4 where k_2 is positive constant

A. Derive the sufficient and necessary condition such that at least one value of Radius(r) exists where the universe is neither expanding nor contracting.

B. Given the values of constant k_1,k_2, and T, find the number of radii possible (only the Cardinal Number) for each set of constants. Constants are given in the datasheet. (https://docs.google.com/spreadsheets/d/1WGqZuoY7H2aJlHMBO0dEUYUEAv_VBp9ekcPKsKxIQho/edit?usp=sharing)

C. Given the values of k_1, k_2, T, and Radius of the universe(R), find whether each of the systems is either expanding, non-expanding, or contracting. By plotting a graph, decide if any of the universes have a stable radius and locate those points. (https://docs.google.com/spreadsheets/d/1rIZaPKV0dqEoe6WCS1gl4n003U-XKv1P3n4Ki2MDfWo/edit?usp=sharing)

Q4. The chronology of the universe is divided into five stages. They are, in chronological order, the very early universe, the early universe, the dark ages and large-scale structure emergence, the universe as it appears today, and the far future and ultimate fate. Each of these stages contains different forms of the universe, some being more dynamic and/or homogenous than others. The Dark Ages are particularly interesting in this context, as their end marked a period that would see the birth of the first generation of stars. **(10 Marks)**

A. Reionization of the Universe is the latter of the two major gas phase transitions in the history of the Universe. Imagine a Universe where there was no reionization after the Dark Ages. How would it be different from our Universe? Comment specifically regarding the following points:
   a. Opacity.
   b. The abundance of large structures (like galaxies and nebulae).
   c. The overall composition of the universe.

B. In comparison to galaxies, the spectrum of quasars lacks sharp spectral lines. Why does this happen? What is the significance of this effect in identifying reionization?

C. In 1944, German Astronomer Walter Baade categorized the Milky Way stars in a special system. In this characterization, some stars are more likely candidates than others in searching for reionization energy sources. Elucidate.

End of Problem Statement