INVESTIGATING THE ROLE OF DARK MATTER AND DARK ENERGY IN THE EVOLUTION OF THE UNIVERSE BASED ON MODERN COSMOLOGICAL OBSERVATIONS

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ABSTRACT

The study of dark matter and dark energy represents one of the most fundamental and unresolved challenges in modern cosmology. These two components are believed to constitute approximately 95% of the total energy density of the Universe, while ordinary baryonic matter accounts for only about 5%. Despite their invisibility in the electromagnetic spectrum, their existence is strongly supported by multiple independent cosmological observations, including galaxy rotation curves, gravitational lensing effects, large-scale structure formation, and cosmic microwave background (CMB) measurements.

Keywords: *Dark Matter, Dark Energy, Cosmology, Universe Expansion, Cosmic Microwave Background, Gravitational Lensing, ΛCDM Model, Galaxy Formation, Supernova Type Ia, Astrophysical Observations.*

INTRODUCTION

Modern cosmology considers dark matter and dark energy as two dominant but fundamentally different components of the Universe. According to the ΛCDM

(Lambda Cold Dark Matter) model, supported by multiple observational datasets, approximately 27% of the Universe is composed of dark matter, about 68% is dark energy, and only around 5% is ordinary baryonic matter. This distribution is not directly observable through electromagnetic radiation, but it is inferred through gravitational and cosmological effects measured by advanced astronomical instruments and missions such as the Planck satellite and large-scale galaxy surveys.

MAIN PART

Dark matter is a non-luminous and non-interacting (except gravitationally) form of matter that plays a fundamental role in the formation of galaxies and large-scale cosmic structures. Its existence was first strongly supported by observations of galaxy rotation curves, notably by Vera Rubin's studies (1970s), where outer stars in galaxies were found to rotate at unexpectedly high velocities, contradicting Newtonian predictions based solely on visible matter.

Modern observations from the Sloan Digital Sky Survey (SDSS, ongoing since 2000) and gravitational lensing measurements confirm that visible matter alone cannot account for observed gravitational effects. Gravitational lensing, particularly weak lensing surveys such as those from the European Space Agency's Euclid mission (launched 2023), shows distortions in light from distant galaxies that can only be explained by the presence of invisible mass distributions.

Dark matter acts as a gravitational "scaffold," allowing baryonic matter to accumulate and form galaxies, galaxy clusters, and filamentary structures known as the cosmic web. Without dark matter, simulations show that the Universe would be far more homogeneous, lacking the complex structure observed today.

The Cosmic Microwave Background radiation is one of the most powerful observational tools in cosmology. Precision measurements by the Planck Collaboration (2018 final data release) provide strong evidence for the existence and proportions of dark matter and dark energy.

CMB anisotropies (tiny temperature fluctuations) reflect the density variations in the early Universe, which later evolved into galaxies and clusters. These fluctuations are consistent only if dark matter is included in cosmological models, as it enhances gravitational collapse without interacting with radiation.

The CMB power spectrum analysis strongly supports the ΛCDM model and constrains the density parameters:

Ω_m (matter density) ≈ 0.31

$\Omega\Lambda$ (dark energy density) ≈ 0.69

These values confirm that dark energy is the dominant component of the Universe today.

The expansion of the Universe is described by the first Friedmann equation:

$H^2 = (\dot{a}/a)^2 = (8\pi G/3)\rho - kc^2/a^2 + \Lambda c^2/3$

Where:

H = Hubble parameter

a(t) = scale factor

ρ = total energy density

k = spatial curvature

Λ = cosmological constant (dark energy term)

G = gravitational constant

From this equation, it becomes clear that cosmic evolution is determined by the competition between attractive gravity (matter + dark matter) and repulsive dark energy (Λ).

Density perturbation growth is described by:

$\delta = \delta\rho/\rho$

Linear perturbation equation:

$d^2\delta/dt^2 + 2H(d\delta/dt) - 4\pi G\rho_m \delta = 0$

Where ρ_m includes baryonic + dark matter.

Growth condition:

$\delta(t) \propto a(t)$ (matter-dominated era)

Dark matter dominates structure formation because it does not interact with radiation pressure, allowing early gravitational collapse.

COSMOLOGICAL EXPERIMENT: DARK MATTER AND DARK ENERGY EFFECTS (PHYSICAL MODEL).

EXPERIMENT STEP	PHYSICAL MODEL / FORMULA	SAMPLE CALCULATION	PHYSICAL CONCLUSION
1. Universe expansion model (Friedmann equation)	$H^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$	$\rho = \rho_{DM} + \rho_b + \rho_\Lambda$	Expansion rate depends on total energy content
2. Energy composition (ΛCDM model)	$\Omega_i = \rho_i/\rho_c$	$\Omega_{DM} = 0.27,\ \Omega_\Lambda = 0.68,\ \Omega_b = 0.05$	Universe is ~95% dark components
3. Critical density	$\rho_c = \frac{3H^2}{8\pi G}$	$H_0 = 70\ km/s/Mpc \Rightarrow \rho_c \approx 9.2 \times 10^{-27}\ kg/m^3$	Defines geometry of the Universe
4. Dark matter density evolution	$\rho_{DM} \propto a^{-3}$	If $a = 2 \Rightarrow$ ρ_{DM} decreases by factor 8	Dark matter dilutes with expansion
5. Structure growth (perturbation equation)	$\ddot{\delta} + 2H\dot{\delta} - 4\pi G\rho_m\delta = 0$	$\delta \sim a(t)$	Dark matter drives galaxy formation

EXPERIMENT STEP	PHYSICAL MODEL / FORMULA	SAMPLE CALCULATION	PHYSICAL CONCLUSION
6. Gravitational lensing	$\alpha = \frac{4GM}{c^2 b}$	Observed: $M_{total} > M_{visible}$	Confirms existence of dark matter
7. Dark energy pressure	$w = \frac{P}{\rho c^2} = -1$	$P_\Lambda = -\rho_\Lambda c^2$	Negative pressure drives acceleration
8. Acceleration equation	$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P/c^2)$	$P_\Lambda < 0 \Rightarrow \ddot{a} > 0$	Universe expansion is accelerating
9. Scale factor (matter era)	$a(t) \propto t^{2/3}$	Example: $t = 8 \Rightarrow a \approx 4$	Gravity-dominated expansion
10. Scale factor (dark energy era)	$a(t) \propto e^{Ht}$	$H = 70 \Rightarrow exponentialgrowth$	Accelerated exponential expansion
11. Hubble parameter evolution	$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$	At $z = 2 \Rightarrow H \uparrow$	Early Universe was matter-dominated
12. Deceleration parameter	$q = \frac{1}{2}\Omega_m - \Omega_\Lambda$	$q = 0.16 - 0.68 = -0.52$	Universe is currently accelerating

CONCLUSION

The mathematical and physical analysis of the Universe based on the ΛCDM cosmological model clearly demonstrates that the evolution of cosmic structures is governed by the dynamic interplay between dark matter and dark energy. Using the

Friedmann equations derived from General Relativity, it becomes evident that the expansion rate of the Universe is directly determined by its total energy density, which includes baryonic matter, dark matter, radiation, and dark energy.

Dark matter plays a fundamental role in the formation and evolution of large-scale structures. Its density evolution follows $\rho_{DM} \propto a^{-3}$, indicating that it behaves as a pressureless component that dilutes with cosmic expansion while still maintaining gravitational influence. Through perturbation growth equations, dark matter is shown to be the primary driver of structure formation, enabling the development of galaxies, clusters, and the cosmic web through gravitational instability.

In contrast, dark energy is characterized by a constant energy density and a negative pressure described by the equation of state $w = -1$. When incorporated into the cosmic acceleration equation, this negative pressure leads to $\ddot{a} > 0$, confirming that the Universe is undergoing accelerated expansion. Observational constraints from the Hubble parameter, Type Ia supernovae, and cosmic microwave background measurements strongly support this behavior.

The combined observational and theoretical framework, including gravitational lensing, large-scale structure surveys, and redshift-dependent Hubble expansion, consistently confirms that the Universe is spatially flat and dominated by dark components. The deceleration parameter further verifies the current accelerating phase, with $q < 0$indicating that dark energy has surpassed matter as the dominant force in cosmic evolution.

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