The Roles of Dark Matter and Dark Energy in Cosmic Expansion

OXQ Editorial (15)

Abstract: Dynamic symmetry offers a transformative lens through which to examine dark matter and dark energy—the invisible forces shaping cosmic evolution. This paper explores how fractal geometries in galaxy distributions align with dark matter's gravitational influence, while symmetry-breaking mechanisms in quantum fields provide insight into dark energy's acceleration of the universe. Drawing on cosmological observations and theoretical models, it argues that dynamic symmetry bridges the microscopic and macroscopic realms, proposing a unified framework for these enigmatic phenomena.

The universe's accelerating expansion, driven by dark energy, and the gravitational scaffolding of dark matter, which binds galaxies, stand as two of cosmology's greatest puzzles. Traditional approaches often treat these forces as distinct, yet dynamic symmetry—a concept rooted in the interplay of structure and spontaneity—suggests they are interconnected manifestations of universal principles. By examining cosmic structures through the lens of symmetry and its transformations, we uncover new perspectives on the nature of these unseen components.

Observations of the cosmic web, a vast network of galaxies, gas, and dark matter, reveal a striking fractal-like structure. Fractals, characterised by self-similar patterns across scales, emerge in systems governed by dynamic symmetry. Surveys such as the Sloan Digital Sky Survey (SDSS) show that galaxy clusters exhibit fractal dimensions between 1.2 and 1.5 at scales below 100 megaparsecs, transitioning to homogeneity at larger distances. This hierarchical clustering mirrors processes seen in turbulent fluids or biological networks, where local interactions generate global order. Dark matter, constituting 27% of the universe's mass-energy, is hypothesised to mould this web through gravitational collapse. Simulations of cold dark matter haloes reproduce these fractal patterns, suggesting that dark matter's influence operates through scale-free gravitational interactions, preserving symmetry across cosmic scales.

The self-similar symmetry (SSS) model formalises this idea, proposing that the universe's structure—from quantum fluctuations to galactic superclusters—follows a geometric sequence tied to the cosmic microwave background (CMB) temperature. This model posits that fundamental constants, such as the gravitational constant and electron mass, evolve in concert with the universe's expansion. For instance, the electron mass (m_e) and gravitational constant (G) are derived as functions of CMB temperature, implying that dark matter's fractal distribution is not arbitrary but governed by symmetry-preserving processes. The cosmic web's filaments, where galaxies coalesce, reflect a balance between gravitational order and quantum-mechanical disorder, a hallmark of dynamic symmetry.

Dark energy, constituting 68% of the universe's energy density, presents a complementary challenge. Observations of Type Ia supernovae and CMB anisotropies indicate that dark energy drives accelerated expansion, acting as a repulsive force counteracting gravity. The cosmological constant, a leading candidate for dark energy, faces a fine-tuning problem: quantum field theory predicts a vacuum energy density 10^120 times larger than observed. Dynamic symmetry addresses this paradox by framing dark energy as a transient phenomenon arising from symmetry breaking. In the SSS model, the cosmological constant scales with the square of the CMB temperature, linking its current value to the universe's thermal history. This scaling suggests that dark energy evolves dynamically, its dominance reflecting a late-time phase transition in the vacuum energy.

Quantum field theories further illuminate this mechanism. Spontaneous symmetry breaking during the electroweak epoch generated the Higgs field's vacuum expectation value, but its gravitational effect was negligible due to cancellations between particle and antiparticle contributions. Residual symmetry-breaking effects, amplified by cosmic expansion, could manifest as dark energy. Recent models propose that dark energy arises from the discharge of a top-form gauge field in a hidden sector, a process analogous to phase transitions in condensed matter. This discharge, occurring at a rate proportional to the Hubble parameter, discretely reduces vacuum energy over time, offering a natural explanation for its small observed value.

Fractal cosmology unifies dark matter and dark energy by integrating their roles in cosmic structure. The cosmic web's fractal geometry, sustained by dark matter's gravitational pull, coexists with dark energy's repulsive force, which drives the expansion of voids. This duality mirrors dynamic symmetry's balance: dark matter imposes order through clustering, while dark energy introduces disorder via expansion. The McGinty Equation, which integrates fractal geometry and quantum-gravitational effects, models this interplay. Fractal potential terms capture dark matter's scale-free clustering, while vacuum energy terms account for dark energy's homogeneous distribution.

Observational evidence supports this synthesis. Planck satellite measurements of CMB temperature fluctuations reveal a spectral index consistent with inflationary models, where quantum fluctuations seed fractal structures. Similarly, baryon acoustic oscillations (BAOs)—regular ripples in galaxy density—serve as cosmic rulers, their spacing determined by dark matter's gravitational wells and dark energy's expansive push. These BAOs exhibit fractal-like regularity, bridging microscopic quantum effects and macroscopic cosmic patterns.

The SSS model also predicts variations in fundamental constants. If G and m_e evolve with CMB temperature, their current values reflect a symmetry-breaking epoch where dark energy became dominant. This evolution aligns with Dirac's Large Numbers Hypothesis, which relates cosmological and microscopic scales through dimensionless ratios. For example, the ratio of the universe's radius to the electron's radius remains invariant under SSS scaling, suggesting a deep symmetry between quantum and cosmic phenomena.

Critically, dynamic symmetry circumvents the cosmological constant problem by framing dark energy as a residual effect of symmetry breaking rather than a static parameter. In symmetry-breaking models, post-cancellation vacuum energy is reduced by a factor of 10^32, matching observational bounds. This residual energy, though minimal, drives cosmic acceleration, its influence amplified over cosmological timescales. Similarly, dark matter's fractal distribution arises naturally from initial quantum fluctuations, avoiding ad hoc assumptions about its particle properties.

Future observations will test these ideas. Euclid and the Vera Rubin Observatory will map galaxy distributions at unprecedented resolution, probing fractal dimensions and BAO scaling. Meanwhile, CMB-S4 and LiteBIRD will refine measurements of CMB temperature and primordial gravitational waves, constraining symmetry-breaking models. Laboratory experiments, such as quantum simulations of fractal potentials, could validate theoretical predictions, bridging cosmology and condensed matter physics.

In summary, dynamic symmetry provides a unified framework for dark matter and dark energy, framing them as complementary facets of cosmic evolution. Fractal geometry and symmetry breaking, operating across scales, resolve longstanding puzzles—from galaxy clustering to vacuum energy—while offering testable predictions for the universe's fate.

References and Further Reading

Pietronero, L. et al. (1987). Fractal Distribution of Galaxies. *Physica A: Statistical Mechanics and Its Applications*.

Cosme, C., Rosa, J.G., & Bertolami, O. (2020). Can Dark Matter Drive Electroweak Symmetry Breaking? *Physical Review D*.

Sonoda, T. (2016). Self-Similar Symmetry Model and Cosmic Microwave Background. *Frontiers in Applied Mathematics and Statistics*.

Kaloper, N. (2025). Discretely Evanescent Dark Energy. *arXiv:2506.04317*.

McGinty, C. (2025). The Beauty of Mathematical Fractals and the Mystery of Dark Matter. *LinkedIn*.

Planck Collaboration (2020). Planck 2018 Results. *Astronomy & Astrophysics*.

Scrimgeour, M.I. et al. (2012). The WiggleZ Dark Energy Survey. *Monthly Notices of the Royal Astronomical Society*.