Identifying Key Drivers of High-Redshift Brightest Cluster Galaxy Evolution Using Machine Learning Techniques

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The assembly of Brightest Cluster Galaxies (BCGs) is commonly attributed to hierarchical mergers at low redshift, yet the mechanisms governing their early-universe growth remain poorly quantified. This study examines the relative influence of internal baryonic processes and environmental accretion at high redshift Brightest Cluster Galaxies using the IllustrisTNG-Cluster simulation. BCG progenitors were tracked from z = 4 to z = 1.5, with a focused analysis of 501 galaxies at z = 3, a physically motivated epoch preceding merger-dominated assembly. A Random Forest regression framework was then developed to identify the drivers of BCG growth across five fundamental indicators: stellar mass, star formation rate, half-mass radius, metallicity, and gas fraction. Model performance was optimized in two stages using R^2 metrics, first by evaluating temporal subsets and then by integrating satellite-based features to isolate environmental effects. Feature importance rankings were then used to interpret the physical pathways through which internal processes regulate stellar mass assembly. Results show that at z = 3, In-situ stellar mass emerges as the primary predictor of mass buildup(Spearman ? = 0.968) and strongly correlates with metallicity(? = 0.886) and gas fraction(? = -0.552), indicating an established gas–star formation–enrichment feedback cycle. Moreover, elevated metallicity is consistent with cooling efficiency and promotes compact structure formation(? = -0.531). Satellite galaxy and external merger contributions remain subdominant at this epoch. These results provide quantitative evidence that high-redshift BCGs evolve primarily as internally regulated systems, refining the merger-centric framework of massive galaxy formation.

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