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Fractional Time-Delayed Cosmology: Memory Effects and the de Sitter Attractor

Time delays provide a natural framework for describing systems in which the response to a physical process is not instantaneous. In a cosmological context, such effects may arise when the dynamics of cosmic fluids involve finite response times. In this work, we investigate a cosmological model based on a time-delayed differential equation for the Hubble parameter. Within Eckart's theory, the bulk viscosity is modeled as $\eta = \eta_0 H(t-T)$, where T denotes the characteristic time delay.

We extend the resulting evolution equation using the last-step approach of fractional calculus by replacing the standard time derivative with a Caputo fractional derivative of order $0 < \alpha < 1$. The cosmological dynamics is therefore governed by
\begin{equation}
{}^{C}D_{t}^{\alpha}H(t)
+\frac{3\gamma}{2}H^{2}(t)
-\eta_{0}H(t-T)
=0.
\end{equation}

The linearized fractional time-delayed equation is solved analytically, while the complete nonlinear system is studied numerically. We analyze the effects of both the fractional order and the time delay on the evolution of the Hubble parameter. Our results show that the solutions evolve toward the de Sitter equilibrium point, providing a cosmological scenario in which fractional dynamics and delayed viscous effects can be incorporated consistently into the late-time evolution of the Universe.

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