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Modified MOND Inertia and Covariant Vacuum State

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Abstract: In this paper, we investigate the inertia of macroscopic objects using a mean field approach. Hence, this approach naturally leads to inertia being described within the framework of thermodynamics. We regard the Hubble constant as the order parameter to describe the overall behavior of the universe. The dynamics are given by the equation of the Kuramoto-like form. The equilibrium solution of the equation is consistent with MOND theory. As a result, the state of the universe at large scales enters local dynamics in small systems, such as galaxies. We also show that the vacuum energy density arising from zero-point fluctuations and symmetry breakings is acceleration-dependent. By requiring that the vacuum state is covariant, all acceleration-dependent vacuum energy should be regarded as non-physical.

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1. Introduction

The universe in its vast complexity harbors profound mysteries that challenge our understanding of fundamental physics. Observations of the flat rotation curves of galaxies reveal a striking discrepancy that galaxies rotate faster than can be accounted for by the visible matter alone, suggesting the presence of an invisible mass, known as dark matter. It is also hypothesized to explain a range of gravitational anomalies observed in gravitational lensing and the cosmic microwave background (CMB) [1]. Despite its success in accounting for these phenomena, the dark matter paradigm faces significant challenges. The lack of direct detection raises questions about its fundamental validity. The most widely accepted Cold Dark Matter (CDM) model struggles to account for observational discrepancies at smaller scales, such as the "missing satellites problem," where the predicted number of dwarf galaxies around massive galaxies exceeds observations [2–4], and the "cusp-core problem," where simulated dark matter halos exhibit central density cusps inconsistent with the flatter density profiles observed in some galaxies [5]. In addition, some observational data including rapid galaxy growth [6]and flat velocity curves extending beyond the expected virial radii of dark matter halos [7] also suggest inconsistencies with the CDM model. These issues imply that the CDM framework may need refinement or that our understanding of gravitational dynamics requires revision.

One such alternative theory is the Modified Newtonian Dynamics (MOND) proposed by Milgrom as a modification to Newtonian gravity at extremely low accelerations [8–10]. Although MOND struggles to account for phenomena at cosmological scales, such as the cosmic microwave background and large-scale structure formation, the simplicity and predictive power of MOND make it a valuable theoretical tool, prompting ongoing research into its foundations and potential extensions. Unlike the dark matter hypothesis, the MOND paradigm stipulates that the observed gravitational effects arise not from unseen mass but from a deviation in the law of gravity when accelerations fall below a critical threshold $a_0 \approx 1.2 \times 10^{-10}\mathrm{m/s}^2$. Milgrom's law can be written as $\mu(a/a_0)a = a_N$, where a_N is the Newtonian acceleration produced by the visible matter, a is the true gravitational acceleration and the interpolating function $\mu(x)$ satisfies $\mu(x) \approx 1$ when $x \gg 1$, and $\mu(x) \approx x$ when $x \ll 1$. In the deep-MOND regime $(a \ll a_0)$, MOND modifies the gravitational force law to scale inversely with distance rather than the square of the distance, effectively reproducing the flat rotation curves of galaxies and Tully-Fisher relation without invoking dark matter. MOND can be interpreted as a modification of gravity or inertia. In the modified gravity interpretation, Newton's law of gravity

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should be modified at low accelerations, leading to a stronger gravitational effect than predicted by the usual inverse-square law. This approach has been formalized in theories such as the Tensor-Vector-Scalar (TeVeS) gravity [11] and bimetric theories [12], which attempts to provide a relativistic extension of MOND [10]. Alternatively, the modified inertia interpretation suggests that the response of a body to a given force depends on the acceleration regime.

Given the empirical validations and elegant mathematical structure of general relativity, there is more potential in modified inertia as the basis for MOND because it seems to be less drastic. Inertia governs how objects respond to applied forces. However, the origin of inertia remains an open question in modern physics. Understanding the origin of inertia could provide critical insights into the foundations of the MOND theory. This paper explores these concepts, aiming to elucidate the fundamental nature of inertia in shaping our understanding of the universe. In classical mechanics, inertia is an intrinsic property of mass, yet its microscopic basis is not well understood. Some theories propose that inertia arises from interactions with the vacuum [13]. Einstein's theory of general relativity offers a partial explanation, suggesting that mass influences and is influenced by the local geometry of spacetime. Alternative perspectives, like Mach's principle, suggest that inertia is a relational property, emerging from an object's interaction with the global distribution of matter in the universe. Instead of introducing some vague concept of the unknown vacuum degrees of freedom, in this paper we fully utilize Mach's principle.

Clearly, the inertial mass of elementary particles primarily arises from the interaction with the Higgs field. For a charged particle, the interaction of particles with the electromagnetic field also contributes to inertia, known as electromagnetic mass. In general, we should consider all possible contributions. On the other hand, for macroscopic objects, various intricate interactions may contribute to the emergence of the inertial mass. But using a mean field theory approach, it is possible to study a system with a large or infinite number of degrees of freedom. Thus we define a mean field that represents the average effect of all the contents of the universe, which is consistent with Mach's principle. This approach naturally leads to inertia being described within the framework of thermodynamics. This may suggest a connection between gravity and thermodynamics. In some studies, gravity is regarded as an entropic force [14–17]. In my personal view, this only means that gravity can be described in another framework at the macroscopic level, whereas at microscopic scales gravity may still be quantum. Furthermore, emergent phenomena at the cluster and cosmological scales arise from the interactions, primarily gravity, of the universe's components. Thus, it is gravity that leads to emergent phenomena at larger scales rather than gravity itself originating from emergence. Additionally, a very noteworthy coincidence is that the value of $a_0 \approx 1.2 \times 10^{-10} \mathrm{m/s}^2$ determined from galaxy dynamics in MOND is of the order of some acceleration constants of cosmological significance. It is of the same order as H_0 (H_0 is the Hubble constant) and $(\Lambda/3)^{1/2}$ (Λ is the cosmological constant). This mysterious "cosmic coincidence" raises questions about its fundamental significance and potential cosmic connections. In this paper, we will investigate the inertia of macroscopic objects and derive the modified acceleration formula based on Mach's principle. As a result, the state of the universe at large scales enters local dynamics in small systems, such as galaxies. In fact, it is a ”synchronization” phenomenon at cosmological scales similar to the Kuramoto model [18,19] and the Hubble constant H_0 can be regarded as the order parameter to describe the overall behavior of the entire universe.

Another concern of this study is the cosmological constant problem, which remain a theoretical puzzle that bridges cosmology and quantum field theory [20]. The problem originates from the interpretation of the cosmological constant Λ as the vacuum energy density. There are at least two sources for the vacuum energy. In the cosmological context, spontaneous symmetry breakings in the early universe may have induced phase transitions, potentially contributing to the vacuum energy density associated with the cosmological constant. Although one can always adjust the vacuum energy today to zero by tuning the parameter of the potential, it is not a very satisfactory method because the vacuum energy cannot be zero before and after the phase transition. In addition, in quantum field theory the vacuum is filled with quantum fluctuations contributing to a zero-point energy (ZPE). Since

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all energy gravitates, it is expected that the ZPE contribute to the cosmological constant. However, the theoretical prediction of the cosmological constant from quantum field theory contrasts with its observed value, giving rise to a discrepancy that spans over 120 orders of magnitude. One promising avenue for addressing the cosmological constant problem is supersymmetry (SUSY), a theoretical framework that posits a symmetry between fermions and bosons [21]. But experimental searches at the Large Hadron Collider have yet to detect supersymmetric particles. In addition, the precise mechanism by which SUSY could resolve the cosmological constant problem remains elusive, as the required cancellations demand an extraordinary degree of fine-tuning in the SUSY-breaking sector. In this paper, we will calculate the vacuum energy for an accelerating observer. An interesting thing happens when we consider the Unruh effect which predicts that an accelerating observer in a vacuum will detect a thermal bath at a temperature proportional to its proper acceleration [22]. In Ref. [23], it has been shown that the electroweak phase transition (EWPT) occurs and the electroweak gauge symmetry can be restored when the acceleration exceeds the critical value as seen from the point of view of an accelerating observer. This means that the Unruh temperature is not just a formal artifact but a real temperature which can give rise to non-trivial thermal effects. We note that requiring that the vacuum state is covariant drives the theoretical value of the vacuum energy density to zero. Our analysis is based on the conservative assumption of maximal validity of quantum field theory and general relativity.

This paper is organized as follows. Sec.2 is dedicated to the inertial mass of macroscopic objects. In Sec.3, we calculate the vacuum energy density by requiring that the vacuum state is covariant. Finally, in Sec.4 we summarize the main results obtained. For convenience, we use natural units with $c = \hbar = k = 1$.

2. Inertia of Macroscopic Objects and MOND

Based on Mach's principle, let us define a mean field that represents the average effect of all the contents of the universe. As a result, this approach naturally leads to inertia being described within the framework of thermodynamics and the system can be characterized by the temperature. Similar to the Kuramoto model [18,19], we can add the acceleration of all contents in the universe to obtain an average acceleration in a specific direction to describe the overall behavior of the universe. However, assuming the universe is isotropic, it is more appropriate to describe the dynamics of the system using a Unruh temperature corresponding to the acceleration. Furthermore, inertial observers in our universe with a positive cosmological constant detect a Gibbons–Hawking radiation with the temperature $T_{\rm GH} = H_0/2\pi$ [24], where H_0 is the current Hubble constant. Therefore, the temperature of the mean field and the order parameter of the entire universe in a "synchronized" state stabilize at the value $T_{\rm GH}$. Every object with an acceleration deviating from H_0 appears to be subjected to a force that drives its acceleration toward H_0. It is a "synchronization" phenomenon at cosmological scales and the overall behavior of the universe encoded in H_0 enters local dynamics in small systems, such as galaxies. The dynamics expressed in terms of the temperature are given by the equation of the following Kuramoto-like form:

$$\dot{T}_U = \frac{1}{2\pi}F_{\rm ext} + \varepsilon T_{\rm GH}\Gamma(T_{\rm GH} - T_U), \tag{1}$$

where the dot denotes the derivative with respect to time t, $T_U = \frac{1}{2\pi}\left(a^2 + H_0^2\right)^{1/2}$ is the Unruh temperature of the radiation seen by a local comoving accelerating observer in de Sitter spacetime, ε is the positive coupling strength, $F_{\rm ext}$ represents the external force applied to the object and $\Gamma(T_{\rm GH} - T_U)$ is a general function for the interaction between the accelerating object of interest and the mean field. We require that Γ satisfies $\Gamma(T_{\rm GH} - T_U) < 0$ when $T_U > T_{\rm GH}$, and $\Gamma(T_{\rm GH} - T_U) > 0$ when $T_U < T_{\rm GH}$. Similar to how elementary particles acquire mass through interaction with the Higgs field, we define the effective inertial mass of macroscopic objects arising from interaction with the mean field as $m_{\rm eff} = \varepsilon T_{\rm GH}$ with $\varepsilon = m_{\rm eff}/T_{\rm GH}$. When T_U is very close to the Gibbons–Hawking temperature $T_{\rm GH}$,

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we can expand Eq. (1) around $T_{\rm GH}$ and retain only the linear terms by using the relation $\Gamma(0) = 0$. The coefficient involving the first derivative of Γ with respect to T_U at $T_U = T_{\rm GH}$ can be absorbed into the definition of $m_{\rm eff}$. Since we have defined the effective inertial mass, external forces can be expressed in the form of Newton's second law, namely $F_{\rm ext} = m_{\rm eff} a_N$ with a_N being the Newtonian expression for the acceleration. Thus Eq. (1) can be written in terms of the acceleration as

$$\frac{a\dot{a}}{\sqrt{a^2 + H_0^2}} = m_{\rm eff}\left[H_0 - \left(a^2 + H_0^2\right)^{1/2}\right] + m_{\rm eff} a_N. \tag{2}$$

The fixed point given by $\dot{a} = 0$ represents stable solutions of Eq. (2) and one arrives at

$$a_N = \left(a^2 + H_0^2\right)^{1/2} - H_0, \tag{3}$$

which leads to $\mu(a/a_0)a = a_N$ with $a_0 = 2H_0$. The result is consistent with Milgrom's hypothesis [13]. If we require that Eq. (1) holds in the deep-MOND regime ($a \ll a_0$), the function Γ should take the form $\Gamma(T_{\rm GH} - T_U) = T_{\rm GH} - T_U$. We can generalize Eq. (1) to the framework of general relativity, where the system is characterized by the curvature scalar rather than temperature. This is merely a geometric version of the dynamics describing "synchronization" phenomena. It was interestingly noted that the local dynamics of small systems depend on the state of the universe at large scales and the Hubble constant varies during the evolution of the universe. Therefore, we should replace H_0 with the varying Hubble parameter $H(t)$. For $a \ll 2H(t)$, the modified acceleration becomes $a = \sqrt{2H(t)a_N}$. It is expected that MOND has a different impact on the evolution of the universe during the periods of inflation and decelerated expansion compared to the present universe. Furthermore, the choice of the cosmic order parameter may not be unique and the key point is that the state at cosmic scales influences the behavior of local systems.

3. Acceleration-Dependent Vacuum Energy

For an accelerating observer the electroweak $SU(2) \times U(1)$ gauge symmetry in the Standard Model is restored for acceleration larger than a critical value. The vacuum expectation value (VEV) v is given by [23]

$$v(a) = v_0\sqrt{1 - \frac{a^2}{a_{\rm EW}^2}}. \tag{4}$$

where v_0 is the VEV for the inertial observer, a is the proper acceleration and $a_{\rm EW}$ is the critical proper acceleration of the EWPT. The second-order phase transition of the restoration of electroweak symmetry occurs at $a_{\rm EW}$ and for $a > a_{\rm EW}$, we have $v = 0$. The elementary particles therefore acquire a acceleration-dependent mass which is

$$m(a) = m_0\sqrt{1 - \frac{a^2}{a_{\rm EW}^2}}, \tag{5}$$

where m_0 is the mass of the elementary particle for the inertial observer. By introducing the Unruh-like temperature:

$$T_{\rm EW} = \frac{a_{\rm EW}}{2\pi} \tag{6}$$

and

$$T(a) = \frac{a}{2\pi}, \tag{7}$$

Eq. (5) can be also written as

$$m(T) = m_0\sqrt{1 - \frac{T^2}{T_{\rm EW}^2}}, \tag{8}$$

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where $T_{\text{EW}} \sim 10^2$ Gev is the critical temperature of the EWPT. It turns out that all massive particles of Standard Model become massless for the local accelerating observer when the acceleration, or equivalently the temperature, exceeds the critical value.

The vacuum energy receives contributions from both zero-point fluctuations and symmetry breakings. We first calculate the ZPE. The ZPE density of a real free scalar field is given by

$$\rho_Z = \frac{1}{(2\pi)^3}\frac{1}{2}\int d^3\boldsymbol{k}\,\omega(k) \tag{9}$$

with

$$\omega(\boldsymbol{k}) = \sqrt{|\boldsymbol{k}|^2 + m_0^2}, \tag{10}$$

where $(\omega, \boldsymbol{k})$ is the four-dimensional momentum and m_0 is the mass of the scalar field. Obviously, the integral is divergent in the ultraviolet region. The common method is to introduce an ultraviolet cut-off Λ_{UV} at the Planck scale, then one obtains $\rho_Z \sim 10^{76}$ GeV^4, which is larger than the observed value of vacuum energy density by a factor of 10^{123}. But careful calculations yield

$$\rho_Z = \frac{\Lambda_{\text{UV}}^4}{16\pi^2} + \frac{m_0^2\Lambda_{\text{UV}}^2}{16\pi^2} + \frac{m_0^4}{64\pi^2}\ln\left(\frac{m_0^2 e^{\frac{1}{2}}}{4\Lambda_{\text{UV}}^2}\right) + \cdots, \tag{11}$$

$$p = \frac{\Lambda_{\text{UV}}^4}{48\pi^2} - \frac{m_0^2\Lambda_{\text{UV}}^2}{48\pi^2} - \frac{m_0^4}{64\pi^2}\ln\left(\frac{m_0^2 e^{\frac{7}{6}}}{4\Lambda_{\text{UV}}^2}\right) + \cdots, \tag{12}$$

where p is the pressure. The Lorentz symmetry of the vacuum requires that the energy density and pressure satisfy the equation of state $p = -\rho_Z$. Notice that the first two terms of Eqs. (11) and (12) break Lorentz invariance and can be removed by local counterterms. Therefore, upon using a regularization scheme that preserves Lorentz symmetry of the vacuum, for any quantum field one arrives at the following expression for the ZPE density [25]

$$\rho_Z = \pm\frac{s m_0^4}{64\pi^2}\ln\left(\frac{m_0^2}{\mu^2}\right), \tag{13}$$

where μ is the renormalization scale, s represents the number of polarization states and the signs $\pm$ are associated with bosons and fermions respectively. The result can be generalized to any other interacting fields by simply replacing m_0 with the renormalized mass m_R. We see that the expression is proportional to the mass of the particle to the power four and the massless particles do not contribute to the ZPE. This result is very different from the result obtained by imposing a Planck cut-off.

Another contribution to the cosmological constant comes from the symmetry breakings. We now calculate the vacuum energy produced by the EWPT at the classical level. We should also consider the QCD symmetry breaking ($\sim 10^{-1}$ Gev) and other symmetry breakings at higher energy scales (e.g., the grand unification scale at 10^{14} Gev and the Planck scale at 10^{19} Gev). However, all these expressions take a similar form and the analysis parallels the electroweak case. The Higgs field consists of two complex scalar fields arranged into a doublet. After the EWPT, the field acquires a VEV and the corresponding vacuum energy density is $\rho_{\text{EW}} = \lambda v^4 \sim 10^8$ Gev^4 with λ being the coupling constant describing the self-interaction of Higgs fields. In addition to being inconsistent with observational data, such a large vacuum energy density corresponding to a large cosmological constant would also produce a high Gibbons–Hawking temperature, thereby triggering a phase transition. From Eq. (4), we see that the vacuum energy density of the EWPT must satisfy the equation:

$$\rho_{\text{EW}} = \rho_0\left(1 - \frac{T_h^2}{T_{\text{EW}}^2}\right)^2\theta(T_{\text{EW}} - T_h), \tag{14}$$

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where ρ_0 is the vacuum energy density in the absence of Gibbons–Hawking radiation, $\theta(x)$ is the Heaviside step function, $T_{\mathrm{EW}} \sim 10^2$ GeV is the EWPT temperature and $T_h = \frac{1}{2\pi}(8\pi G\rho_s/3)^{1/2}$ is the Gibbons–Hawking temperature produced by the huge vacuum energy density ρ_s of symmetry breakings. When the vacuum energy density exceeds 10^{10} GeV^4, the broken electroweak symmetry is restored and ρ_{EW} vanishes. The backreaction can drive Λ back to zero, even when the vacuum energy density experiences large disturbances extending to the Planck scale because large disturbances will lead to a phase transition and restoration of the symmetry.

It is worth noticing that all the vacuum energy is acceleration-dependent and hence observers with different accelerations will measure different vacuum energy when quantum effects enter the stage. The key point is that the vacuum energy derived from zero-point fluctuations and symmetry breakings is not real if we require the vacuum state to be covariant. Therefore, for a potential covariant theory of quantum gravity, we should define a vacuum that is invariant for all observers and arbitrary coordinate transformations. Although the inertial mass arising from the interaction between the particle and the Higgs field depends on the acceleration and vanishes for an observer exceeding the acceleration threshold, we can extract the covariant part of the mass arising from other interactions. If we interpret the current cosmological constant Λ as the vacuum energy density $\rho_{vac} \sim 10^{-47}$ Gev^4 and assume that Λ arises from the covariant part of the electromagnetic mass, using Eq. (13), the electromagnetic mass of an charged particle such as an electron for an inertial observer is approximately 10^{-3} ev.

4. Conclusions

In this paper, we investigate the inertia of macroscopic objects with a huge number degrees of freedom. The system is drastically simpler by using a mean field theory approach. Meanwhile, this approach naturally leads to inertia being described within the framework of thermodynamics. We then calculate the vacuum energy density based on quantum field theory. It turns out that the vacuum energy is acceleration-dependent when quantum effects enter the stage. Here, we calculate the vacuum energy density arising from symmetry breaking at the tree level. If quantum corrections are considered, one only needs to replace it with the Coleman-Weinberg effective potential [26]. However, the result is the same because quantum corrections also depend on acceleration. Since we are considering gravitational effects, by requiring a covariant vacuum as demanded by general relativity, all acceleration-dependent energy should be regarded as non-physical. An intriguing conjecture is that the current cosmological constant may arise from the covariant electromagnetic mass and hence the electromagnetic mass of an charged particle such as an electron is approximately 10^{-3} ev. However, this guess needs a further exploration.

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