A Network-Based Microscopic Interpretation of Vacuum Localised Structures

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Abstract

Vacuum Localised Structures (VLS) have recently been proposed as self-gravitating solutions of the Einstein field equations. Such structures have been investigated in connection with galactic dark matter distributions, filamentary gravitational configurations, and black-hole-like vacuum solutions without baryonic matter sources. Although the corresponding solutions are mathematically consistent within General Relativity, the physical interpretation of the underlying stress-energy tensor remained unclear.

In the present work, a microscopic interpretation of VLS structures is explored using a dynamical network framework. Space is interpreted as an emergent structure arising from an underlying discrete connectivity network, in which effective metric properties are associated with local link configurations and shortest-path relations. Curvature is interpreted as a spatial variation of effective network connectivity.

Within this framework, a VLS is described as a self-sustained coherent network configuration maintained by local reconnection dynamics.

This surface-dominated dynamical behaviour naturally leads to the effective equation of state in which the radial pressure equals minus one-third of the energy density, thereby providing a possible microscopic interpretation of the peculiar stress-energy properties associated with VLS solutions.

Keywords

Vacuum Localised Structures, General Relativity, Pregeometry, Cosmology, Dark Matter Alternatives

1. Introduction

The nature of dark matter remains one of the central unresolved problems in modern astrophysics and cosmology. Observational evidence from galactic rotation curves, gravitational lensing, galaxy clusters, and large-scale structure formation strongly suggests the presence of additional gravitational effects beyond visible baryonic matter [1-5]. The standard cosmological model generally assumes the existence of one or more new particle species beyond the Standard Model of particle physics. However, despite extensive experimental efforts, no direct detection of dark matter particles has yet been confirmed.

An alternative possibility is that the observed gravitational phenomena may originate from self-organised vacuum structures allowed within General Relativity itself. In previous work, the author investigated gravitational vacuum configurations referred to as Vacuum Localised Structures (VLS), previously also denoted as gravitational geons [6] or vacuum bubbles [7]. These structures were studied in several contexts, including galactic dark matter distributions

[6], filamentary gravitational configurations [8], and black-hole-like vacuum solutions without baryonic matter sources [9].

In particular, it was shown that stable or quasi-stable gravitational structures may exist for an effective equation of state of the form:

$$p_r = -\alpha\,\rho \tag{1}$$

where p_r denotes radial pressure, ρ the energy density and α = 1/3. The tangential pressure p_t follows from equilibrium considerations. Only at the center of the VLS, the radial and the tangential pressure are equal. Note that a larger value of α leads to a repulsive region at the center (negative Tolman density) and is therefore excluded. Such an equation of state differs significantly from ordinary matter, radiation, or vacuum energy, and therefore requires further physical interpretation.

Previous investigations mainly focused on the corresponding gravitational solutions and their astrophysical implications. However, the microscopic origin of the associated stress-energy tensor has remained largely unexplored. The purpose of the present paper is not to propose a complete microscopic theory of spacetime or quantum gravity, but rather to investigate whether a simple network-based framework can provide a physically intuitive interpretation of the VLS concept and its characteristic equation of state.

In the proposed approach, spacetime geometry is interpreted as an emergent property of an underlying discrete connectivity network composed of nodes and links. Effective metric properties arise from shortest-path relations and local connectivity distributions within the network. Variations in network connectivity correspond to effective curvature in the continuum limit. Similar ideas have appeared in several approaches to discrete or emergent spacetime, including causal networks, spin-network approaches, graph-based geometries, and emergent gravity models [10–15].

The approach presented here is intended as a heuristic microscopic interpretation of VLS structures rather than as a complete fundamental description of spacetime. Nevertheless, it may provide useful physical insight into the origin and stability of self-gravitating vacuum configurations in General Relativity.

2. Network Interpretation

2.1 Fundamental Network Structure

The starting point of the present approach is the assumption that spacetime geometry may emerge from an underlying discrete connectivity structure composed of elementary nodes and links. At the microscopic level, no continuous coordinates or differentiable manifold are assumed a priori. Instead, the fundamental structure is represented by a graph-like network.

A central assumption of the present framework is that the microscopic network is not static. Instead, the network continuously evolves through local reconnection processes involving nodes and links.

At the microscopic level, elementary processes include:

- creation of links through node splitting

- annihilation of links through node merging

The vacuum state itself may then correspond to a statistical equilibrium configuration of these microscopic update processes.

A connection between two nodes $i$and j is represented by an adjacency matrix:

$$A_{ij} = \begin{cases} 1 & \text{if nodes } i \text{ and } j \text{ are connected} \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

The local connectivity of a node is characterised by its degree:

$$d_i = \sum_j A_{ij} \tag{3}$$

where d_i represents the number of direct links associated with node i.

Within this framework, spatial relations are not fundamental but emerge from the connectivity structure itself. A natural notion of effective distance between two nodes is obtained from the shortest-path length through the network. The effective discrete distance between nodes $i$and $j$is therefore defined as:

$$d(i,j) = \min\left(\sum_{\text{path}} w_{kl}\right) \tag{4}$$

where w_{kl} denotes the weight associated with a link between nodes k and l, and the summation is performed along the shortest weighted path connecting i and j.

The shortest-path structure therefore plays the role of an emergent metric relation.

2.2 Emergent Metric Properties

To recover an effective continuum description, consider a local neighbourhood surrounding a node p. Nearby nodes may be associated with effective coordinate directions through local classes of links or through a local embedding procedure. For sufficiently small separations, the squared shortest-path distance may be approximated by an effective quadratic form

$$ds^2 \approx g_{\mu\nu}\, dx^\mu dx^\nu \tag{5}$$

where $g_{\mu\nu}$ represents an emergent effective metric tensor.

Within the network interpretation, the effective metric components are associated with the local connectivity properties of the underlying node-link structure. A local effective connectivity tensor $C_{\mu\nu}(i)$ may be constructed from the directional distribution of links in the neighbourhood of node i. If $e_\mu^{(a)}$ denotes the effective local direction associated with link a, and w_a its corresponding weight, one may define

$$C_{\mu\nu}(i) = \sum_{a\in N(i)} w_a\; e_\mu^{(a)} e_\nu^{(a)} \tag{6}$$

where the summation is restricted to links belonging to a local neighbourhood surrounding node i.

Since larger local connectivity corresponds to shorter effective shortest-path distances, the emergent metric tensor is expected to scale approximately with the inverse of the connectivity tensor:

$$g_{\mu\nu} \propto (C^{-1})_{\mu\nu}. \tag{7}$$

Uniform connectivity corresponds to an approximately flat geometry, while spatial variations in connectivity generate effective curvature. Anisotropic connectivity distributions naturally produce anisotropic metric properties. In this picture, geometry is not fundamental but emerges statistically from the underlying connectivity structure of the network.

In the isotropic continuum limit, the local connectivity tensor may be approximated by

$$C_{\mu\nu}(x) \approx \rho(x)\,\delta_{\mu\nu}, \tag{8}$$

where $\rho(x)$ represents an effective local connectivity density and $\delta_{\mu\nu}$ is the Euclidean metric tensor. The emergent metric then reduces to the conformally flat form

$$g_{\mu\nu}(x) = \Omega^2(x)\,\delta_{\mu\nu}, \tag{9}$$

with

$$\Omega^2(x) \propto \frac{1}{\rho(x)}. \tag{10}$$

Within this approximation, regions of high connectivity correspond to smaller effective spatial scales, while regions with lower connectivity correspond to an effective stretching of space.

2.3 Curvature as Connectivity Variation

In General Relativity, curvature arises from spatial variations of the metric tensor. In the present framework, such variations emerge from changes in the underlying network connectivity.

A perfectly homogeneous network with approximately constant local connectivity corresponds to an approximately flat emergent geometry. Deviations from uniform connectivity generate variations in effective shortest-path structure and therefore produce effective curvature.

A useful discrete measure of local connectivity variation may be introduced through the graph Laplacian

$$L_{ij} = D_{ij} - A_{ij}, \tag{11}$$

where A_{ij} is the adjacency matrix and D_{ij} is the diagonal degree matrix,

$$D_{ij} = \begin{cases} d_i & \text{if } i = j, \\ 0 & \text{if } i \neq j. \end{cases} \tag{12}$$

The graph Laplacian measures local differences between the connectivity of neighbouring nodes and therefore provides a natural discrete analogue of differential curvature operators in the continuum limit.

The present approach does not attempt to derive General Relativity from first principles. Instead, the objective is only to establish a qualitative correspondence between local connectivity variations and effective spacetime curvature.

Within this interpretation, gravitational curvature is not viewed as a fundamental continuous property of spacetime itself, but rather as an emergent large-scale manifestation of local variations in microscopic network connectivity.

In continuum General Relativity, spacetime curvature is described by the Einstein field equations

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}, \tag{13}$$

where $R_{\mu\nu}$ is the Ricci tensor, R the Ricci scalar, $g_{\mu\nu}$ the metric tensor, and $T_{\mu\nu}$ the stress-energy tensor.

Within the present framework, the effective metric tensor emerges from the local connectivity structure of the underlying network. In the isotropic continuum approximation, spatial variations in the effective connectivity density $\rho(x)$ lead to spatial variations in the conformal factor $\Omega(x)$, thereby generating effective curvature in the emergent geometry.

We consider a spatial metric of the conformal form

$$g_{ij}(x) = \Omega^2(x)\, \delta_{ij}, \tag{14}$$

where δ_{ij} is the flat Euclidean metric and $\Omega(x)$ is a local scale factor determined by the underlying node-link structure of the network.

In the present framework, the conformal factor is assumed to be related to the local link density $\rho(x)$ through

$$\Omega^2(x) = \frac{\rho_0}{\rho(x)}, \tag{15}$$

where ρ_0 is a reference density. Here $\rho(x)$ denotes the effective local connectivity density of the network, defined as the average number of links per node within a local coarse-graining region surrounding the point x. The quantity therefore measures the local degree of network interconnectedness rather than the spatial density of nodes themselves. Regions with a high density of links therefore correspond to smaller local spatial scales, while regions with fewer links correspond to an effective stretching of space.

If Ω is spatially constant, the metric reduces to a globally rescaled Euclidean geometry and the space remains flat. Curvature only appears when Ω varies with position. The essential point is that curvature depends not merely on the value of Ω, but on how rapidly it changes across space.

An intuitive analogy may be made with an ordinary surface: first derivatives describe slopes, while second derivatives describe curvature. Similarly, in the present model, $\nabla\Omega$ describes the spatial variation of the scale factor, whereas $\nabla^2\Omega$ describes the variation of that variation and is therefore directly related to curvature.

To simplify the analysis, it is convenient to introduce the logarithmic variable

$$\phi(x) = \ln \Omega(x). \tag{16}$$

This substitution linearizes many derivative expressions because

$$\partial_i \Omega = \Omega\ \partial_i \phi. \tag{17}$$

For a conformally flat metric in three dimensions, the Ricci scalar curvature is determined by derivatives of the conformal factor. At the schematic level, the Christoffel symbols behave as

$$\Gamma \sim \partial g, \tag{18}$$

and since $g_{ij} = \Omega^2 \delta_{ij}$, one obtains schematically;

$$\Gamma \sim \partial\Omega/\Omega = \partial(\ln\Omega) \tag{19}$$

The Ricci curvature is constructed from derivatives and quadratic combinations of Christoffel symbols,

$$R \sim \partial\Gamma + \Gamma^2 \tag{20}$$

where the full tensor expression, including index contractions and numerical factors, is omitted here for simplicity. This leads (schematically) to:

$$R \sim \partial^2(ln\,\Omega) + (\partial \ln\Omega)^2. \tag{21}$$

Expressed in terms of $\phi = \ln\Omega$, this becomes

$$R \sim \nabla^2\phi + (\nabla\phi)^2. \tag{22}$$

In the regime where spatial variations are sufficiently smooth,

$$(\nabla\phi)^2 \ll \nabla^2\phi, \tag{23}$$

the quadratic gradient term may be neglected, yielding the approximate relation (up to convention-dependent numerical factors and signs)

$$R \sim \nabla^2\phi. \tag{24}$$

Substituting

$$\phi = \ln\Omega = -\tfrac{1}{2}\ln\rho + \text{constant}, \tag{25}$$

gives

$$R(x) \propto -\ \nabla^2 \ln\rho(x). \tag{26}$$

This relation provides a direct connection between geometry and the underlying network structure: spatial curvature emerges from spatial variations in the logarithm of the local link density. While similar differential structures arise naturally in conformal geometry, the present interpretation associates the conformal field directly with the microscopic connectivity properties of the underlying node-link network.

Physically, this implies that gravity is not introduced as an independent field imposed on space, but rather emerges from inhomogeneities in the connectivity structure of the underlying network. Uniform link density corresponds to flat space, whereas regions where the density changes non-uniformly generate effective curvature.

Although the present discussion is formulated primarily at the scalar level through the Ricci scalar R, the underlying geometric structure remains fully tensorial. The metric $g_{ij} = \Omega^2(x)\delta_{ij}$

defines the complete Levi-Civita connection and therefore uniquely determines the full Riemann curvature tensor $R^{i}{}_{jkl}$, the Ricci tensor R_{ij}, and the associated scalar curvature R. The scalar relation derived below should therefore be regarded as a reduced isotropic approximation capturing the dominant dependence of curvature on spatial variations in the link-density field $\rho(x)$. In a fully anisotropic network, directional dependence of the link structure would generally lead to nontrivial tensor components beyond the scalar curvature alone.

3. Vacuum Localised Structures as Coherent Network Configurations

Within the framework developed in the previous chapter, a Vacuum Localised Structure (VLS) may be interpreted as a self-sustained coherent configuration of the underlying connectivity network. In this picture, the VLS does not correspond to ordinary baryonic matter, but rather to a dynamically organised region in which the local connectivity structure differs from that of the surrounding vacuum network.

The essential idea is that the vacuum itself may admit locally stable or quasi-stable connectivity configurations capable of producing effective gravitational curvature. Such structures may therefore act as gravitational sources without requiring conventional matter components.

In the continuum limit, these organised network regions correspond to effective stress-energy distributions satisfying the Einstein field equations. Previous work has shown that stable gravitational configurations may exist for an effective equation of state of the form $p_r = -1/3\ \rho$.

A VLS is interpreted as a local departure from this equilibrium state. The structure is maintained dynamically through continuous microscopic reconnection activity which preserves the large-scale coherence of the configuration.

4. Equation of state of the vacuum in a VLS

In frameworks where spacetime, matter, and the gravitational field emerge from a discrete dynamical network of nodes and links governed by local rewrite rules (including node merging, splitting, and link rewiring), the Vacuum Localised Structures (VLS) proposed by Van Nieuwenhove admit a natural microscopic interpretation. These structures are characterized by a static, spherically symmetric metric sourced by an anisotropic stress-energy tensor,

$$T^{\mu}_{\nu} = \mathrm{diag}(-\rho\,, p_r, p_t, p_t) \tag{27}$$

with a Gaussian energy density profile

$$\rho(r) = \rho_0 e^{-\left(\frac{r}{R}\right)^2} \tag{28}$$

and a radial equation of state

$$p_r = -(1/3)\,\rho. \tag{29}$$

The tangential pressure p_t is determined via the conservation condition $\nabla_\mu T^{\mu}_{\ r} = 0$ and generally differs from p_r, reflecting the broken isotropy. Within the network picture, a VLS corresponds to a large-scale, self-stabilized, spherically symmetric excitation in the background network activity. The emergent spacetime volume is generated by the statistical distribution and dynamics of nodes (fundamental atoms of space) and links (encoding adjacency or causal relations). The Gaussian density profile arises as an equilibrium configuration in which the local node density is highest near the center and falls off radially, sustained by a position-dependent balance of merge and split processes. The radial negative pressure state $p_r = -(1/3)\,\rho$ can be understood as a statistical bias in the rewrite rules: when radial links become stretched or the local node density decreases (due to curvature or expansion), the probability of node-splitting and new link insertion along the radial direction increases. This preferential creation of new network elements radially outward acts as an effective inward tension that resists dilution of the node density. The specific factor of 1/3 emerges naturally from the three-dimensional spherical geometry, in which radial expansion corresponds to one degree of freedom while the network balances creation rates against the two tangential directions, yielding an effective equation-of-state parameter analogous to (but opposite in sign from) that of radiation.

In contrast, the tangential pressures p_t reflect different local statistics. Tangential shells experience higher coordination numbers and reconnection rates, particularly in regions of steep density gradient. This can lead to regimes of positive p_t (effective outward momentum flux from frequent local rewiring) near the center and potentially tension-like behavior at larger radii, consistent with the sign changes in p_t (r) permitted by the conservation equations in the VLS model. The overall structure remains gravitationally attractive because the Tolman mass integral, involving the combination $\rho + p_r + 2\, p_t$, stays positive, producing flat rotation curves and core-like density profiles without invoking particulate dark matter. Localization and stability arise because the radial creation bias counteracts outward dilution while central high-activity regions maintain equilibrium through balanced merge/split events. Such configurations can be viewed as network solitons or persistent large-scale fluctuations, smoothly embedded in the homogeneous background vacuum (where isotropic rules yield the global $p = -\rho$ equation of state).

While speculative, the picture demonstrates how anisotropic vacuum stresses with $p_r = -\,(1/3)\,\rho$ can arise mechanistically in pre-geometric models and motivates further investigation into network rules capable of reproducing the Einstein equations with anisotropic vacuum sources in the continuum limit.

The emergent energy density ρ in a dynamic network structure acquires a clear microscopic interpretation. Energy density corresponds to the local intensity of network activity, quantified by the average rate of rewrite operations per unit emergent volume together with the associated density of sustained nodes and links. Each fundamental update carries an intrinsic "action cost" in the underlying discrete dynamics; the time-averaged frequency and complexity of these processes at a given emergent region directly source the positive energy density observed in the continuum limit. For the vacuum, this activity takes the form of a statistically uniform background of transient fluctuations. Virtual particles, as familiar from quantum field theory, find a natural analogue as short-lived, coordinated local states of the network: brief clusters of nodes and links that form through splitting and rewiring events, interact via local rules, and subsequently annihilate through merging, returning to the background. These virtual excitations are not permanent entities but statistical fluctuations whose average occurrence rate per unit volume yields a constant vacuum energy density. Because the rewrite rules are designed (or naturally evolve) to maintain a statistically uniform fluctuation intensity, the vacuum energy density remains independent of emergent volume. As the network expands, new nodes and links are generated at a rate that precisely compensates for dilution, providing the microscopic origin of the vacuum equation of state $p = -\rho$.

Ordinary matter differs fundamentally in the character and persistence of network excitations. While vacuum fluctuations consist of ephemeral, balanced merge-split cycles that largely cancel at large scales, ordinary matter arises from topologically stable or long-lived defects and coherent structures in the network. These may include persistent defects such as knotted link configurations, stable vortex-like rewiring patterns, or regions with systematically altered coordination numbers and rewrite biases. Such structures carry a net topological charge or conserved quantity (e.g., baryon number or spin) that prevents rapid annihilation. In contrast to vacuum fluctuations:

- Matter contributes a positive energy density primarily through the persistent presence and sustained activity required to maintain these stable defects.
- The associated pressure is typically positive because the coherent structures induce frequent local momentum exchanges (effective “collisions” or repulsive rewiring interactions) between neighboring network elements, producing net outward momentum flux.

This distinction yields a unified mechanism: both vacuum and matter energy densities originate from network activity, but vacuum energy is sustained by homogeneous, transient, self-regenerating fluctuations (leading to constant and negative pressure), whereas ordinary matter arises from localised, topologically protected, persistent excitations (leading to diluting density and generally positive pressure).

5. Conclusions

In the present work, a possible microscopic interpretation of Vacuum Localised Structures (VLS) has been explored using a discrete network-based framework. The primary objective was not to construct a complete theory of spacetime or quantum gravity, but rather to investigate whether the unusual stress-energy properties associated with VLS configurations may emerge naturally from an underlying dynamical connectivity structure.

The proposed framework assumes that spacetime geometry is not fundamentally continuous, but instead emerges from a microscopic network of nodes and links. Effective spatial distances are associated with shortest-path relations within the network, while local variations in connectivity generate effective curvature in the continuum limit.

Within this interpretation, Vacuum Localised Structures correspond to self-organised coherent network configurations maintained through continuous microscopic reconnection dynamics. The Vacuum Localised Structures (VLS) analyzed in this work are based on an anisotropic vacuum equation of state characterized by a radial pressure $p_r = -\frac{1}{3}\rho$, with the tangential pressure p_t determined self-consistently from the conservation equations. This specific choice corresponds to a minimal vacuum-dominated regime that yields stable, gravitationally attractive configurations capable of reproducing flat galactic rotation curves and resolving the core-cusp problem without requiring particulate dark matter. In the underlying dynamical network framework, this radial equation of state emerges naturally from a statistical bias in the local rewrite rules, whereby stretched radial links preferentially trigger node-splitting events, with the factor of $1/3$ arising from the geometric distinction between the single radial direction and the two tangential directions in spherically symmetric configurations.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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