The quantum, the geon and the crystal: new insights from non-Riemmanian geometry on modified gravity

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Gravity, the quantum, and the geon

- It is generally believed that at high enough energies General Relativity (GR) will be superseded by a quantum theory of gravity.
  - Planck length: $l_P \equiv \sqrt{\frac{\hbar G}{c^3}} \simeq 10^{35} m$
  - Quantum Gravitational regime: $R^{\alpha}{}_{\beta\gamma\delta} \simeq 1/l_P^2$

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  - Quantum Gravitational regime: $R^{\alpha}{}_{\beta\gamma\delta} \simeq 1/l_P^2$
- Quantum Physics suggests dramatic changes at the Planck scale:
  - Uncertainty relations in the measurement of space-time $\rightarrow$ Non-commutative geometry?
  - The energy of the probing particles could form black holes $\rightarrow$ The end of particle physics?
  - Is the continuum approach still valid? $\rightarrow$ Quantized geometry?
  - Is the field approach in 4D still valid? $\rightarrow$ String theories?

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- Effective descriptions through classical models might be necessary and, in fact, they could serve as a guide for developing the underlying fundamental theories.
- Existence of singularities in GR is both conceptually and operationally disturbing. One could thus . . .
    1. live with the existence of these singularities in the metric,
    2. postulate that quantum theory somehow regularizes the metric,
    3. look for self-consistent descriptions of the notion of body within classical GR.

- The concept of GEON (self-consistent gravitational electromagnetic entity) was introduced by J. A. Wheeler in 1955 as “self-consistent gravitational electromagnetic entities”.
- Bodies should be described as singularity-free self-gravitating fields.

PHYSICAL REVIEW VOLUME 97, NUMBER 2 JANUARY 15, 1955

Geons*

John Archibald Wheeler
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received September 8, 1954)

Associated with an electromagnetic disturbance is a mass, the gravitational attraction of which under appropriate circumstances is capable of holding the disturbance together for a time long in comparison with the characteristic periods of the system. Such gravitational-electromagnetic entities, or “geons”; are analyzed via classical relativity theory. They furnish for the first time a completely classical, divergence-free, self-consistent picture of the Newtonian concept of body over the range of masses from $\sim 10^{39}$ g to $\sim 10^{57}$ g. Smaller geons are quantum objects whose analysis would call for the treatment of characteristic new effects. Topics of equations of self-consistent geon; mass and radius values. 4. Transformations and interactions of electromagnetic geons; evaluation of refractive index barrier penetration integral for spherical geon; photon-photon collision processes as additional mechanism for escape of energy from system; restatement in language of coupling of characteristic modes; the thermal geon; comparison of gravitation and virtual electron pair phenomena as sources of coupling between modes; gravitational coupling and collective vibrations of geon; fission of a geon; interaction between two geons simple at large distances; orientation dependence and

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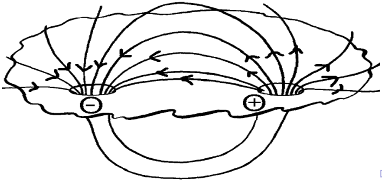
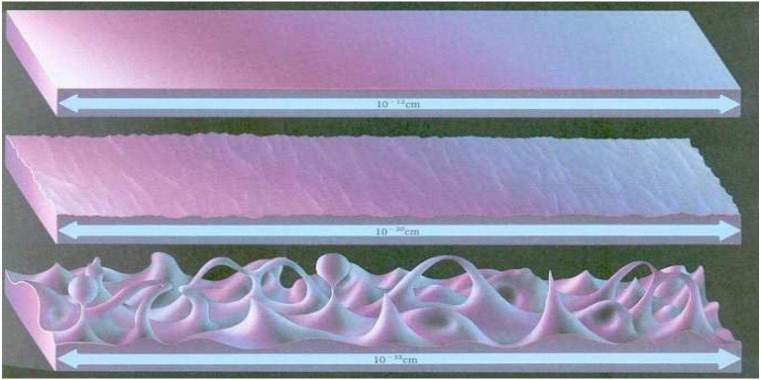
- Combining the concepts of geon with that of multiply-connected topology, Morris and Wheeler (1957) showed that through a wormhole a sourceless electromagnetic field can create mass and charge.
- Self-gravitating geons and non-Euclidean topologies are classical concepts with potential non-trivial consequences for quantum gravity.



- Geons play a role within a larger picture: space-time foam. If topology change could occur dynamically:
  - The smoothness of Minkowskian space would disappear at Planckian scales.
  - Quantum fluctuations would lead to creation annihilation of wormholes.
  - Fluxes through wormholes could be seen as elementary particles



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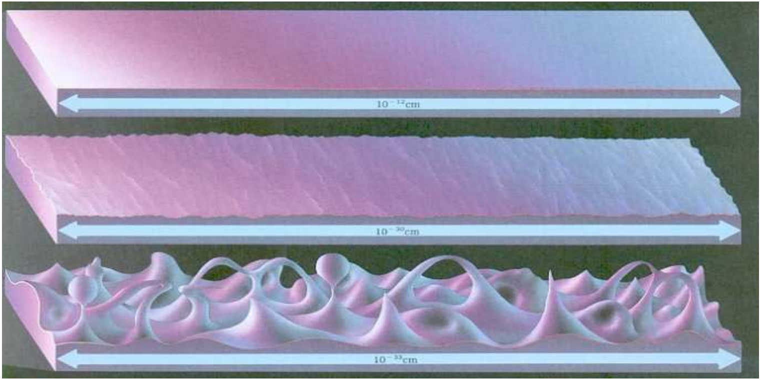
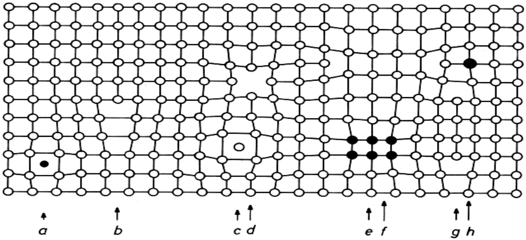


- What kind of framework should we use to describe this scenario?

Lessons from crystalline structures

- A microstructure with topological defects and a macroscopic continuum limit:
  - Is what the idea of space-time foam suggests.
  - Is what we find in crystalline structures (Bravais crystals).



a) Interstitial impurity atom, b) Edge dislocation, c) Self interstitial atom
d) Vacancy, e) Precipitate of impurity atoms, f) Vacancy type dislocation loop,
g) Interstitial type dislocation loop, h) Substitutional impurity atom

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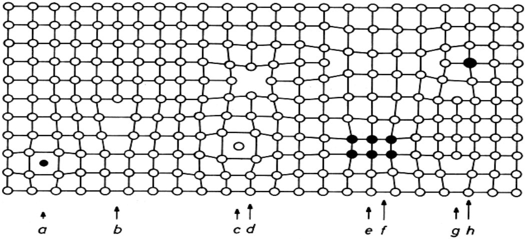

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- In real crystals, the density of defects is generally non-zero.
- There are interactions between different kinds of defects.
- Defects have dynamics: Upon the action of forces or heat, defects can move and interact.

- The continuum differential geometry of crystals is naturally described in terms of a metric-affine space

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  - At each point we find 2 or 3 lattice vectors defining the microstructure.
  - Moving along those vectors we jump from atom to atom.
  - Distances can be measured by step counting along crystallographic directions:

$$ds^2 = g_{ij} dx^i dx^j$$

    with $g_{ij} = \delta_{ij}$ and $\Gamma^a_{bc} = 0$ in suitable coordinates
  - An affine connection $\Gamma^\lambda_{\mu\nu}$ is used to transport vectors and define geodesics.

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- Important lessons from crystalline structures:
    - Perfect crystals may have Euclidean or Riemannian geometry.
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    - Point defects imply non-metricity: $Q_{\lambda\alpha\beta} = \nabla_\lambda g_{\alpha\beta} \neq 0$: step-counting is no longer possible

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- Systems with defects require a non Riemannian description.

- Action of modified gravity

$$S = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}f(g_{\mu\nu}, R^{\alpha}{}_{\beta\mu\nu}) + S_m[g_{\mu\nu}, \Psi]$$

is constructed with contractions of the Riemann tensor with the metric to produce invariants such as with $g_{\mu\nu}R^{\mu\nu}$, $R_{\mu\nu}R^{\mu\nu}$ ($R_{\mu\nu} = R^{\rho}_{\mu\rho\nu}$) and $R^{\alpha}{}_{\beta\mu\nu}R_{\alpha}{}^{\beta\mu\nu}$.

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- Palatini field equations: obtained by independent variation with respect to metric and connection: two systems of equations.
- The connection equations read

$$\nabla_{\mu}(\Sigma^{\alpha}{}_{\beta}g^{\beta\gamma}) = 0$$

where the matrix $\hat{\Sigma}$ (only depends on the matter!) measures the non-metricity. Introduce a rank-two tensor $h_{\mu\nu}$ associated to a Levi-Civita connection $\Gamma^{\lambda}_{\mu\nu}$: $\nabla^{\Gamma}_{\mu}(\sqrt{-h}h^{\alpha\gamma}) = 0$.

- In terms of $h_{\mu\nu}$ we obtain Einstein-like equations

$$R_{\mu}{}^{\nu}(h) = \frac{1}{\sqrt{det\Sigma}}\left(\frac{f}{2}\delta_{\mu}^{\nu} + \kappa^2 T_{\mu}{}^{\nu}\right)$$

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- In many cases of interest the relation between $h_{\mu\nu}$ and $g_{\mu\nu}$ can be algebraically found and involves only the matter $\rightarrow$ the field eqs. for $g_{\mu\nu}$ are also second-order.

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- In vacuum $R_{\mu}{}^{\nu} = \Lambda\delta_{\mu}^{\nu}$ which are deSitter solutions $\rightarrow$ these theories have the same number of propagating d.o.f. as GR.
- This procedure provides a full solution for a given gravity Lagrangian and physical scenario.

Palatini geons

- Palatini Born-Infeld theory

$$S^{BI} = \frac{1}{\kappa^2 \varepsilon} \int d^4x \left[\sqrt{-|g_{\mu\nu} + \varepsilon R_{\mu\nu}(\Gamma)|} - \lambda \sqrt{-g} \right] + S_m$$

where $\varepsilon \propto l_P^2$ (the quantum).

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- Vacuum field equations

$$R_{\mu\nu}(q) = \frac{(\lambda-1)}{\lambda\varepsilon}q_{\mu\nu} \leftrightarrow R_{\mu\nu}(g) = \frac{(\lambda-1)}{\varepsilon}g_{\mu\nu}$$

- The vacuum EOM boil down to GR+Λ (with $\Lambda \equiv \frac{(\lambda-1)}{\varepsilon}$)
  - No higher-order field equations.
  - No ghosts propagating in vacuum.
  - At first order, BI gravity recovers quadratic gravity:

$$S \approx \int \frac{d^4x\sqrt{-g}}{2\kappa^2}\left[R-2\Lambda_{eff}-\frac{\varepsilon}{2}\left(-\frac{R^2}{2}+R_{\mu\nu}R^{\mu\nu}\right)+\ldots\right]$$

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  - Exact solutions corresponding to electrovacuum fields ("Reissner-Nordström solutions") can be obtained

- In ingoing Eddington-Finkelstein coordinates

$$ds^2 = -A(x)dv^2 + \frac{2}{\sigma_+}dvdx + r^2(x)d\Omega^2$$

where

$$\begin{aligned} A(x) &= \frac{1}{\sigma_+}\left[1 - \frac{r_S}{r}\frac{(1+\delta_1 G(r))}{\sigma_-^{1/2}}\right] \\ \delta_1 &= \frac{1}{2r_S}\sqrt{\frac{r_q^3}{l_P}} \\ \sigma_\pm &= 1 \pm \frac{r_c^4}{r^4(x)} \\ r^2(x) &= \frac{x^2+\sqrt{x^4+4r_c^4}}{2} \end{aligned}$$

where $r_c = \sqrt{l_P r_q}$, and $r_q^2 = 2G_N q^2$ is a length scale associated to the electric charge. $G(z)$, with $z = r/r_c$ can be written as an infinite power series expansion of the form

$$G(z) = -\frac{1}{\delta_c} + \frac{1}{2}\sqrt{z^4-1}\left[f_{3/4}(z) + f_{7/4}(z)\right]$$

where $\delta_c \approx 0.572069$.

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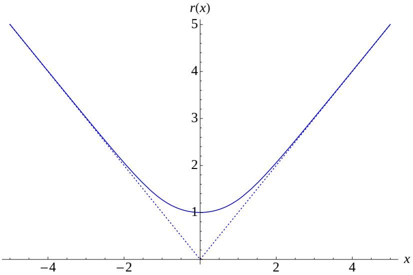
- For $\delta_1 = \delta_c$ the geometry is completely regular $\rightarrow$ it can be extended to the region $x < 0$.

- The radial coordinate behaves as a wormhole geometry



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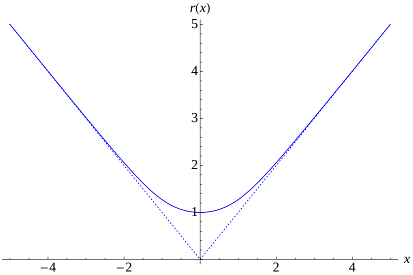

- An electric flux flowing through the wormhole mouth suffices to define an electric charge without charges. The density of flux has universal properties
- This defines a geon in Wheeler's sense.

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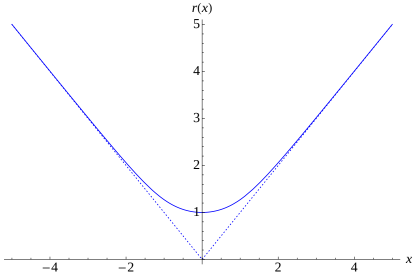

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- The wormhole is present even in those cases with curvature divergences ($\delta_1 \neq \delta_c$)? $\rightarrow$ geodesic completeness analysis is needed! (in progress).

Conclusions

- The metric-affine EiBI-Quadratic gravity has unexpected high-energy phenomenology:
  - GR equations are recovered *always* in vacuum.
  - Geons arise in different Palatini gravities (1207.6004 [gr-qc], 1311.0815 [hep-th], 1406.1205 [hep-th])...
  - ...they can have phenomenological implications (1306.2504 [hep-th], 1306.6537 [hep-th], 1402.5099 [hep-th])...
  - ...be generated through topology change (1311.5712 [hep-th],1403.0105 [hep-th])...
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  - ...and have further applications (1405.0208 [hep-th], 1405.7184 [hep-th], 1411.0897 [hep-th])
- In relation with solid state structures, note that:
  - Perfect (Riemannian) structures do not exist in nature.
  - The existence of point defects generates non-metricity.
  - The point defect mass can be estimated according to the difference of volume between the defected and non-defected structure...

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