Dynamical Space: Supermassive Galactic Black Holes and Cosmic Filaments

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The unfolding revolution in observational astrophysics and cosmology has lead to numerous puzzles: "supermassive" galactic central black holes, galactic "dark matter" halos, relationships between these black hole "effective" masses and star dispersion speeds in galactic bulges, flat spiral galaxy rotation curves, cosmic filaments, and the need for "dark matter" and "dark energy" in fitting the Friedmann universe expansion equation to the supernovae and CMB data. Herein is reported the discovery of a dynamical theory for space which explains all these puzzles in terms of 3 constants; G, α - which experimental data reveals to be the fine structure constant $\alpha \approx 1/137$, and δ which is a small scale distance, perhaps a Planck length. It is suggested that the dynamics for space arises as a derivative expansion of a deeper quantum foam phenomenon. This discovery amounts to the emergence of a unification of space, gravity and the quantum.

1 Dynamical Space

The many mysteries of cosmology, such as supermassive galactic black holes, cosmic filaments, "dark matter" galactic haloes, flat spiral-galaxy rotation curves, "dark energy" effects in expansion of the universe, and various unexplained correlations between galactic black hole masses and star velocities, all suggest that we have an incomplete account of space and gravity. We report herein the discovery of such a theory and its successful testing against the above phenomena, and as well against laboratory and geophysical gravity experiments. If space is, at a deep level, a quantum system, with dynamics and structure, then we expect a derivative expansion would give a classical/long-wavelength account. In the absence of that quantum theory we construct, phenomenologically, such an account in terms of a velocity field [1]. In the case of zero vorticity we obtain

$$\nabla\cdot\left(\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v}\right) + \frac{\alpha}{8}\left((trD)^2 - tr(D^2)\right) + \\ + \frac{\delta^2}{8}\nabla^2\left((trD)^2 - tr(D^2)\right) + ... = -4\pi G\rho$$

$$\nabla\times\mathbf{v} = \mathbf{0}, \quad D_{ij} = \frac{\partial v_i}{\partial x_j} \tag{1}$$

where the major development reported herein is the discovery of the significance of the new δ−term, with δ having the dimensions of a length, and presumably is the length scale of quantum foam processes. This term is shown to be critical in explaining the galactic black hole and cosmic filament phenomena. This δ is probably a Planck-like length, and points to the existence of fundamental quantum processes. If $\delta = 0$ (1) cannot explain these phenomena: δ must be non-zero, no matter how small, and its value cannot be determined from any data, so far. G is Newton's constant, which now appears to describe the dissipative flow of quantum foam into matter, and α is a dimensionless self-coupling constant, that experiment reveals to be the fine structure constant, demonstrating again that space is fundamentally a quantum process. We briefly outline the derivation of (1). Relative to the non-physical classical embedding space, with coordinates $\mathbf{r}$, and which an observer also uses to define the velocity field, the Euler constituent acceleration of the quantum foam is

$$\mathbf{a} = \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} \tag{2}$$

and so, when $\alpha = 0$ and $\delta = 0$, (1) relates this acceleration to the density of matter ρ, and which will lead to Newton's account of gravity. The matter acceleration is found by determining the trajectory of a quantum matter wavepacket. This is most easily done using Fermat's maximum proper-travel time τ:

$$\tau = \int dt \sqrt{1 - \frac{\mathbf{v}_R^2(\mathbf{r}_0(t), t)}{c^2}} \tag{3}$$

where $\mathbf{v}_R(\mathbf{r}_o(t), t) = \mathbf{v}_o(t) - \mathbf{v}(\mathbf{r}_o(t), t)$, is the velocity of the wave packet, at position $\mathbf{r}_0(t)$, wrt the local space. This ensures that quantum waves propagating along neighbouring paths are in phase, and so interfere constructively. This maximisation gives the quantum matter geodesic equation for $\mathbf{r}_0(t)$

$$\mathbf{g} = \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} + (\nabla\times\mathbf{v})\times\mathbf{v}_R \\ - \frac{\mathbf{v}_R}{1 - \frac{\mathbf{v}_R^2}{c^2}}\frac{1}{2}\frac{d}{dt}\left(\frac{\mathbf{v}_R^2}{c^2}\right) + ... \tag{4}$$

with $\mathbf{g} \equiv d\mathbf{v}_o/dt$. The 1st term in $\mathbf{g}$ is the Euler space acceleration $\mathbf{a}$, the 2nd term explains the Lense-Thirring effect, when the vorticity is non-zero, and the last term explains the precession of orbits. In the limit of zero vorticity and neglecting relativistic effects (1) and (4) give

$$\nabla \cdot \mathbf{g} = -4\pi G\rho - 4\pi G\rho_{DM}, \quad \nabla \times \mathbf{g} = \mathbf{0} \qquad (5)$$

where

$$\rho_{DM} \equiv \frac{\alpha}{32\pi G}\left((trD)^2 - tr(D^2)\right) + \frac{\delta^2}{32\pi G}\nabla^2\left((trD)^2 - tr(D^2)\right) + ... \qquad (6)$$

This is Newtonian gravity, but with the extra dynamical terms which has been used to define an effective "dark matter" density. This ρ_{DM} is not a real matter density, of any form, but is the matter density needed within Newtonian gravity to explain dynamical effects caused by the α and δ-terms in (1). It is purely a space/quantum-foam self-interaction effect. Eqn.(3) for the elapsed proper time maybe written in differential form as

$$d\tau^2 = dt^2 - \frac{1}{c^2}(d\mathbf{r}(t) - \mathbf{v}(\mathbf{r}(t), t)dt)^2 = g_{\mu\nu}(x)dx^\mu dx^\nu \qquad (7)$$

which introduces a curved spacetime metric $g_{\mu\nu}$ for which the geodesics are the quantum matter trajectories when freely propagating through the quantum foam. When $\alpha = 0$ and $\delta = 0$, and when ρ describes a sphere of matter of mass M, (1) has, external to the sphere, a static solution $\mathbf{v}(\mathbf{r}) = -\sqrt{2GM/r}\hat{\mathbf{r}}$, which results in Newton's matter gravitational acceleration $\mathbf{g}(\mathbf{r}) = -GM/r^2\hat{\mathbf{r}}$. Substituting this $\mathbf{v}(\mathbf{r})$ expression in (7), and making the change of time coordinate

$$t \to t' = t - \frac{2}{c}\sqrt{\frac{2GMr}{c^2}} + \frac{4GM}{c^3}\tanh^{-1}\sqrt{\frac{2GM}{c^2 r}}, \qquad (8)$$

(7) becomes the standard Schwarzschild metric, and which is the usual explanation for the galactic black hole phenomenon, see [3–5], namely a very small radius but very massive concentration of matter. To the contrary we show here that the observed galactic black holes are solutions of (1), even when there is no matter present, $\rho = 0$. These solutions are quantum foam solitons.

The above $\mathbf{v}(\mathbf{r}) = -\sqrt{2GM/r}\hat{\mathbf{r}}$ solution also explains why the $\alpha-$ and $\delta-$terms in (1) have gone unnoticed, namely that for these solutions $(trD)^2 - tr(D^2) = 0$. It is for this reason that the $\alpha-$ and $\delta-$terms are now included, namely that Newton's inverse square law for gravity is preserved for solar system situations, and from which Newton determined his theory from Kepler's analysis of Brahe's planetary data. The key point is that the solar system is too special to have revealed the full complexity of the phenomenon of gravity.

However just inside a planet the $\alpha-$term becomes detectable, and it results in the earth's matter acceleration g being slightly larger than that predicted by Newtonian gravity, and we obtain from (1)

$$\Delta g = g_{NG}(d) - g(d) = -2\pi\alpha G\rho(R)d + O(\alpha^2), \quad d > 0 \qquad (9)$$

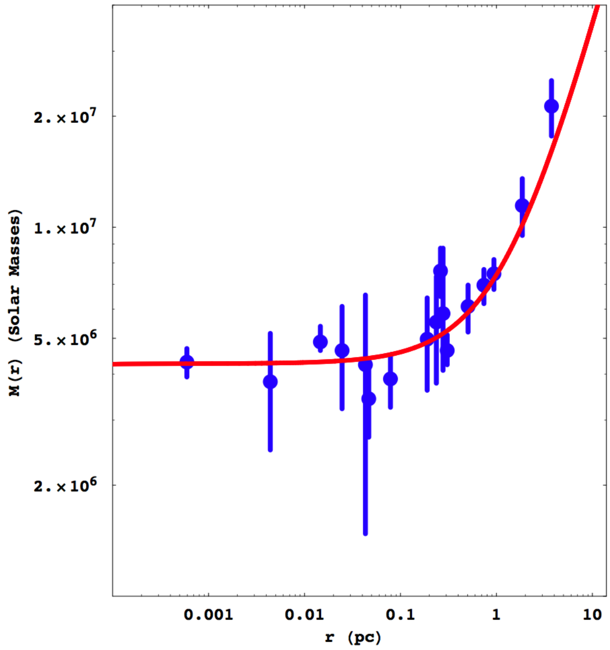

Fig. 1: The $M(r)$ data for the Milky Way SgrA* black hole, showing the flat regime, that mimics a point-like mass, and the rising form beyond $r_s = 1.33$pc, as predicted by (12), but where M_0 and r_s parametrise a quantum foam soliton, and involves no actual matter. The left-most data point is from the orbit of star S2 - using the Ghez *et al.* [3] value $M_0 = 4.5 \pm 0.4 \times 10^6$ solar masses. The other data is from Camenzind [5], but which requires these remaining data points to be scaled up by a factor of 2, presumably arising from a scaling down used to bring this data into agreement with a smaller initial value for M_0.

down a bore hole at depth d. This involves only α as the δ-term is insignificant near the surface. The Greenland Ice Shelf bore hole data [6] and Nevada bore hole data [7], both give $\alpha \approx 1/137$ to within observational errors, even though the ice and rock densities $\rho(R)$ differ by more than a factor of 2 [2]. So this result for α is robust, and shows that α is the fine structure constant $\alpha = e^2\hbar/c$, with α probably the more fundamental constant, and now showing up in the quantum foam account for gravity. As well laboratory measurements of G, modified Cavendish experiments, have always shown anomalous and inconsistent results [10, 11], revealing a systematic effect not in Newtonian gravity. Indeed the Long 1976 laboratory experiment to measure G, reported the anomaly to have magnitude $\delta_L = 0.0037 \pm 0.0007$ [8] (this δ_L is not related to δ in (1)), which equals $0.5/(136 \pm 26)$, showing that α can be measured in laboratory gravity experiments, of the type pioneered by Long.

1.1 Black Holes and Filaments as Quantum Foam Solitons

For the special case of a spherically symmetric flow, and in the absence of matter $\rho = 0$, we set $\mathbf{v}(\mathbf{r}, t) = \hat{\mathbf{r}}v(r)$. Then (1) has exact static two-parameter, v_0 and $\kappa \geq 1$, solutions

$$v(r)^2 = v_0^2(\kappa - 1)\frac{\delta}{r}\left(1 - {}_1F_1\left[-\frac{1}{2} + \frac{\alpha}{4}, -\frac{1}{2}, -\frac{r^2}{\delta^2}\right]\right) + \\ + v_0^2\kappa\left(\frac{4-2\alpha}{3}\right)\frac{r^2}{\delta^2}\frac{\Gamma(\frac{2-\alpha}{4})}{\Gamma(-\frac{\alpha}{4})}\,{}_1F_1\left[1 + \frac{\alpha}{4}, \frac{5}{2}, -\frac{r^2}{\delta^2}\right], \quad (10)$$

where ${}_1F_1\,[a, b, w]$ is the confluent hypergeometric function. Here v_0 is a speed that sets the overall scale, and κ is a structural parameter for the black hole, and sets the relative significance of the two terms in (11) and (12), and which is determined by the history of the black hole: in-falling matter increases κ, and values of both v_0 and κ are affected by surrounding matter if $\rho \neq 0$. In the limit $r \gg \delta$

$$v(r)^2 \approx A\frac{\delta}{r} + B\left(\frac{\delta}{r}\right)^{\alpha/2}. \quad (11)$$

However $v(r) \to 0$ as $r \to 0$ when $\delta \neq 0$, and so the δ-term dynamics self-regulates the interior structure of the black hole, which has a characteristic radius of $O(\delta)$. Inside this radius the in-flow speed goes to zero, and so there is no singularity. Hence there is a naturally occurring UV cutoff mechanism. Eqn. (**??**) gives an asymptotic form for $g(r)$, which is parametrised by an "effective mass" $M(r)$ within radius r: $g(r) = GM(r)/r^2$. In terms of observable $M(r)$ (11) gives a two-parameter description

$$M(r) = M_0 + M_0\left(\frac{r}{r_s}\right)^{1-\alpha/2} \quad (12)$$

r_s is the distance where $M(r_s) = 2M_0$. $M(r)$ from the Milky Way SgrA* black hole [3–5] is shown in Fig.1, and the best fit gives $r_s = 1.33$pc. This remarkable data comes from observations of orbits of stars close to SgrA*, and in particular the star S2, which has an elliptical orbit with a period of 15.2±0.11 years, and is the left-most data point in Fig.1. This dynamical space solution exhibits an effective point-like mass acceleration for $r < r_s$, where $M(r)$ is essentially constant, and for $r > r_s$ an increasing $M(r)$. At the outer-most data point the presence of stars within the galactic core begin to become apparent, with $M(r)$ becoming larger than the form predicted in (12). Note that if $\delta = 0$, then the flat feature in $M(r)$ is absent, while if $\alpha = 0$ the rise in $M(r)$ is absent, and the flat feature continues outwards. Intriguingly then the role of the $\delta-$term dynamics is critical to the effective point-like mass description of the inner region of the black hole, even though there is no actual matter present. It is this region of $M(r)$ that explains the inner star elliptical orbits - with $\delta = 0$ the $\alpha-$term produces a "weak" black hole, but with $g(r) \sim 1/r^{1+\alpha/2}$, which does not produce the observed star orbits. Eqn. (12) is in terms of observables. If we best-fit the data using an $M(r)$ directly from (10), by varying v_0, κ and δ, we find that there is no unique value of δ - v_0 and κ rescale to compensate for a deceasing δ, in the regime outside of the inner core to the black hole, but δ cannot be set to zero. This is evidence of the existence of a finite, but very small, structure to space, suggestive of a Planck-like fundamental length.

This black hole also explains the so-called "dark matter" halo. Asymptotically $\rho_{DM}(r)$ is related to the matter-less $M(r)$ via

$$M(r) = \int_0^r 4\pi r^2 \rho_{DM}(r)dr \quad (13)$$

giving

$$\rho_{DM}(r) = \frac{(1-\alpha/2)M_0}{4\pi r_s^{1-\alpha/2} r^{2+\alpha/2}} \quad (14)$$

which decreases like $r^{-\gamma}$ with $\gamma = 2 + \alpha/2$. The value of the exponent γ has been determined by gravitational lensing for numerous elliptical galaxies in the Sloan Lens ACS Survey [12], and all give the generic result that $\gamma = 2$. Higher precision data may even permit the value of α to be determined. So the space dynamics completely determines ρ_{DM} in terms of observables M_0 and r_s.

Unlike the point-mass parametrisation of black holes, the above shows that the quantum foam black hole is an extended entity, dominating the galaxy from the inner regions, to beyond the central bulge, and even beyond the spiral arms. Indeed the $\rho_{DM}(r)$ in (14) predicts flat rotation curves, with orbital speed given by

$$v_{orb}^2(r) = GM_0\left(\frac{r_s}{r}\right)^{\alpha/2}\frac{1}{r_s} \quad (15)$$

but to which must be added the contribution form the matter density. For the Milky Way, we get the black hole contribution is $v_{orb} = 117$km/s at the location of the solar system, $r = 8$kpc, and determined by M_0 and r_s. That the black hole is an extended structure explains various observed correlations, such as that in [9] which reported a correlation between M_0 and the stellar speed dispersion in the bulge.

Eqn. (1), but only when $\delta \neq 0$, also has exact filament solutions

$$v(r)^2 = v_0^2\frac{r^2}{\delta^2}\,{}_1F_1\left[1 + \frac{\alpha}{8}, 2, -\frac{r^2}{2\delta^2}\right] \quad (16)$$

where r is the distance perpendicular to the axis of the filament, and $v(r)$ is the in-flow in that direction. In the limit $r \gg \delta$

$$v(r)^2 \sim 1/r^{\alpha/4} \text{ giving } g(r) \sim 1/r^{1+\alpha/4} \quad (17)$$

producing a long range gravitational attraction. Such cosmic filaments have been detected using weak gravitational lensing combined with statistical tomographic techniques. Again $v(r) \to 0$ as $r \to 0$ when $\delta \neq 0$, and so the δ-term dynamics self-regulates the interior structure of the filament, which has a characteristic radius of $O(\delta)$.

1.2 Expanding Universe

The dynamical 3-space theory (1) has a time dependent expanding universe solution, in the absence of matter, of the Hubble form $v(r,t) = H(t)r$ with $H(t) = 1/(1+\alpha/2)t$, giving a scale factor $a(t) = (t/t_0)^{4/(4+\alpha)}$, predicting essentially a uniform expansion rate. This results in a parameter-free fit to the supernova redshift-magnitude data. In contrast the Friedmann model for the universe has a static solution - no expansion, unless there is matter/energy present. However to best fit the supernova data fictitious "dark matter" and "dark energy" must be introduced, resulting in the ΛCDM model. The amounts $\Omega_\Lambda = 0.73$ and $\Omega_{DM} + \Omega_M = 0.27$ are easily determined by best fitting the ΛCDM model to the above uniformly expanding result, without reference to the observational supernova data. But then the ΛCDM has a spurious exponential expansion which becomes more pronounced in the future.

2 Conclusions

The notion that space is a quantum foam system suggests a long-wavelength classical derivative-expansion description, and inspired by observed properties of space and gravity, such an effective field theory has been determined. This goes beyond the Newtonian modeling in terms of an acceleration field description - essentially the quantum foam is accelerating, but at a deeper level the acceleration is the Euler constitutive acceleration in terms of a velocity field. This velocity field has been detected experimentally, with the latest being from spacecraft earth-flyby Doppler shift data [13]. The dynamics of space now accounts for data from laboratory experiments through galactic black holes and filaments, to the expansion of the universe. We note that there is now no known phenomenon requiring "dark energy" or "dark matter". The black hole and cosmic filament phenomena require the existence of both α - the fine structure constant, and δ which is presumably a quantum foam characteristic Planck-like length scale. Gravity is now explainable as a emergent phenomenon of quantum foam dynamics, but only if we use as well a quantum wave description of matter - gravitational attraction is a quantum matter wave refraction effect, and also causes EM wave refraction. Hence the evidence is that we are seeing the unification of space, gravity and the quantum, pointing to a revolution in physics, and in our understanding of reality.

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