Back to the Future:

Rise of the Scalar Field
and its
Implications for Interstellar Travel

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Approach

- Survey of modern scalar fields in physics
- through the lens of the Friedmann equation, the workhorse equation of modern cosmology
- parameterizes mysterious forces operating on galactic scales

Force Field Taxonomy

Field Name	Typical Symbol	Transformation	Example	Number of field values at each point
Scalar	Φ	Same in all frames	Newtonian gravitational field	1
Vector	A^{μ}	(dx'/dx)	Electromagnetic field	4
Tensor	$g_{\mu\nu}$	$(dx'/dx)^2$	Relativistic gravitational field	10

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Newtonian Friedmann Equation

Consider a self-gravitating sphere of mass *M* and radius *R(t)*

$$\frac{d^2R}{dt^2} = -\frac{GM}{R^2}$$

Evaluate the first integral

$$\frac{1}{2}\left(\frac{dR}{dt}\right)^2 = \frac{GM}{R} + U_0$$

Introduce $M \equiv \frac{4\pi}{3}\rho R^3$ and $R \equiv a(t)r$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{2U_0}{r^2}\frac{1}{a^2}$$

Friedmann Equation - 1922

from the field equations of general relativity, for the case of a spherically symmetric expanding spacetime.

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\epsilon(t) + \cancelto{0}{\frac{\kappa c^2}{R_0^2}\frac{1}{a^2(t)}}$$

The energy density ϵ can come from radiation, matter, dark energy, or a cosmological constant.

The second term is due to spacetime curvature; our universe appears to be perfectly flat, so this term is set to zero.

Field Equations of General Relativity 1916

spacetime curvature

stress-energy

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

Gravity is a tensor field $g_{\mu\nu}$ with 10 values at every point in spacetime.

Spherical symmetry simplifies $g_{\mu\nu}$ to a single component – like a Newtonian field

$$\nabla^2 \phi = 4\pi G \rho$$

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The Cosmological Constant - 1917:
a constant scalar field

Einstein's ad hoc addition to the field equations of general relativity to “explain” a static universe; then renounced after Hubble's discovery of an expanding universe.

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

The value of Λ is the same everywhere, and corresponds to energy in the vacuum

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2} \epsilon(t) + \frac{\Lambda}{3}$$

Counter-acts gravity, inflating spacetime

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The Brans-Dicke Theory - 1961:

a (contrived) Machian scalar field for G

A scalar field assumed to depend on the mass density of the universe

$$\nabla^2 \phi = \beta T^M$$

Identified with the gravitational constant

Enters the field equations of gravity, contributing to spacetime curvature

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{1}{\phi} \alpha T^M_{\mu\nu} + T^{\phi}_{\mu\nu}$$

Assumed *not* to enter the equations of motion

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Dark Matter:

a scalar field in the equations of motion

motion of galaxies in clusters (1933)

$$\frac{1}{2}v_G^2 = \frac{G\,M_v}{R_C} + \frac{G\,M_D}{R_C}$$

rotation of galaxies (1970)

$$\frac{v_R^2}{R_G} = \frac{G\,M_v}{R_G^2} + \frac{G\,M_D}{R_G^2}$$

hot gas in clusters

$$\frac{dP}{dr} = -\frac{GM_v\rho_g}{r^2} - \frac{GM_D\rho_g}{r^2}$$

Inflation - 1980:

a scalar field at the moment of creation

To explain 3 problems in observational cosmology:
the horizon problem, the flatness problem, and the monopole problem

A cosmological constant drives exponential expansion early in the universe

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{\Lambda_I}{3} \Rightarrow a(t) \propto e^{H_I t}$$

A scalar field emerges from the vacuum to dominate the Friedmann equation for a split second after the Big Bang

$$\ddot{\phi} + \frac{\dot{a}}{a}\dot{\phi} = -\eta c^3 \frac{dV}{d\phi}$$

Dark Energy - 1998:
return of the cosmological constant

Supernovae seen at z ≈ 0.5 are about ¼ magnitude fainter than they should be in a universe without a cosmological constant

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{\Lambda_D}{3} \Rightarrow a(t) \propto e^{H_D t}$$

Observations are parameterized in terms of a general equation of state for the dark energy substance, but observations are consistent with a cosmological constant.

$$P_D = -(0.94 \pm 0.1)\,\epsilon_D$$

Current Model Universe: ΛCDM

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\left[\epsilon_{rad} + \epsilon_{Mdark} + \epsilon_{Mvis} + \epsilon_{infl}\right] + \frac{\Lambda_D}{3}$$

$\epsilon_{infl} \propto \text{cnst} \times \delta(t - t_I)$	Inflation scalar field dominant 10^{-35} seconds after the Big Bang	
$\epsilon_{rad} \propto \frac{1}{a^4}$	Radiation dominant first 50,000 years	$\Omega_{rad} = 8 \times 10^{-5}$
$\epsilon_{dark} \propto \epsilon_{vis} \propto \frac{1}{a^3}$	Matter dominant from 50K to 10B years	$\Omega_{Mdark} = 0.27$ $\Omega_{Mvis} = 0.05$
$\Lambda_D \propto \text{const}$	Dark energy dominant after 10B years (now)	$\Omega_D = 0.68$

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Back to the Future – 1921, 1948

Kaluza unification of gravity and EM

Apply the vacuum equations of general relativity to a five-dimensional metric

$$\tilde{R}_{ab} - \frac{1}{2}\tilde{g}_{ab}\tilde{R} = 0$$

$$\tilde{g}_{ab} = \left[\begin{array}{c|c} g_{\mu\nu} + k^2\phi^2 A_\mu A_\nu & k\phi^2 A_\mu \\ \hline k\phi^2 A_\nu & \phi^2 \end{array}\right]$$

gravity

scalar field

electromagnetism

Kaluza Field Equations – 1948

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} \phi^2 T^{EM}_{\mu\nu} + T^{\phi}_{\mu\nu}$$

Scalar stess energy can explain dark matter or dark energy

Scalar field controls coupling of gravity to EM

$$\nabla^{\mu} F_{\mu\nu} = -3 F_{\mu\nu} \partial^{\mu} \ln \phi$$

$$\nabla^2 \phi = \frac{4\pi G}{c^4} \phi^3 F_{\mu\nu} F^{\mu\nu}$$

Electromagnetic fields are sources to the scalar field

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Historical Narrative

- The first modern unified field theory joined general relativity and electromagnetism
- This theory was not pursued because it predicted a scalar field that was otherwise unknown, and general relativity was thought to be only an approximation to some quantum theory.

- General relativity has since defied unification with any other field
- Precision cosmology has revealed that scalar fields dominate the universe

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Implications for Interstellar Travel

The discovery of cosmic scalar fields suggests a coupling between electromagnetism and gravity

Electromagnetic control of gravity

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

A hyperspace dimension

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu + \phi^2 \left(k A_\nu dx^\nu + dx^5 \right)^2$$

Electromagnetic control of gravity
is necessary for
human control of gravity

Backup

Prediction and Verification

Equations of motion from a 5D geodesic hypothesis

$$\tilde{U}^b \tilde{\nabla}_b \tilde{U}^a = 0$$

Electric charge is *not* a Lorentz scalar

$$q + 4\sqrt{\frac{\pi G}{c^3}}\, m A_\nu U^\nu = constant$$

Different scale factor for radiation-dominated universe

$$a \propto t^{2/5} \quad \text{vs} \quad a \propto t^{1/2}$$

Further Work

- The 5D theory has not been developed for sources; the Maxwell sources and Einstein sources are missing
- Examine electromagnetic control of the 5D interval, for 4D faster-than-light implications
- Explore sensible relaxations of the cylinder condition

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