An imaginary temperature far away from a stationary spinning star

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Stationary axisymmetric perfect fluid solution

We model a rigidly rotating star surrounded by asymptotically flat vacuum. Metric is of the form

$$g = g_{ab}dx^a dx^b = -Vdt^2 + 2Wdtd\phi + Xd\phi^2 + \overline{g} \quad (1)$$

where $\overline{g} = e^{2\mu}(d\rho^2 + Zdz^2)$, $\rho = \sqrt{VX + W^2}$, and V, W, X, μ, Z are functions of ρ and z. $X = 0$ on the axis and $X > 0$ elsewhere.

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Except for the occasional mentions of the universe, our spacetime is globally regular having space topology $\mathbb{R}^3$ and having no ergoregion.

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This means test particles with “zero angular momentum ” move along trajectories whose angular velocity relative to a stationary observer at infinity is $\omega = d\phi/dt$. Such an observer has 4-velocity $\frac{\partial}{\partial t}$ in his proper frame. ω is not the angular velocity of the fluid measured by the same observer.

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It is known that in thermal equilibrium the fluid moves rigidly, the temperature τ is constant along an integral curve of u^a, and that K^a is a Killing vector field. τ is the temperature in the rest frame of the fluid.

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If we write

$$K^a \frac{\partial}{\partial x^a} = \frac{\partial}{\partial t} + \Omega \frac{\partial}{\partial \phi} \qquad (2)$$

then rigid rotation corresponds to a constant Ω inside the star.

Tolman's equation

The Killing vector K^a then extends outside the star to the whole of the stationary axisymmetric vacuum exterior. Inside the star τ^{-1} is the redshift factor so that

$$\tau = +\left(V - 2W\Omega - X\Omega^2\right)^{-1/2} \tag{3}$$

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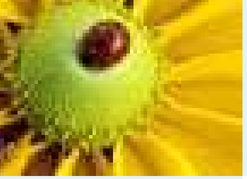
The above equation (modulo a constant fixing the unit of the temperature) is a generalization of Tolman's equation $\tau\sqrt{-g^{00}} =$ constant for a fluid at rest.



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One has $K^aK_a = g\left(\frac{\partial}{\partial t} + \Omega\frac{\partial}{\partial\phi}, \frac{\partial}{\partial t} + \Omega\frac{\partial}{\partial\phi}\right) = -V + 2W\Omega + X\Omega^2$. In the fluid this becomes $K^aK_a = -\tau^{-2} \Leftrightarrow u^au_a = -1$.

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If the fluid extends to infinity asymptotic flatness condition that $V \to 1$, $W \to 0$ and $X = O\left(\rho^2\right)$ give $\Omega = 0$.

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Ω is called the angular velocity of the fluid element measured by a stationary observer in the asymptotically flat region in his rest frame.

g-temperature in the exterior defined

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For any constant β, $\frac{\partial}{\partial t} + \beta \frac{\partial}{\partial \phi}$ is a Killing vector field of the spacetime metric of Eq. (1). It is only that in the exterior we choose a β which has a meaning on the surface of the star. Since we are overlooking how the star and the exterior came to be attached, we are overlooking the history of this vector field. But that should not belittle the fact that this vector field is special.

Diffusion coefficient and Einstein relation

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We suppose that we are in the asymptotic tail end far from the singularity in Eq. (3) so that we can consider locally the temperature to be constant.

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Assuming roughly that the g-temperature is constant, and assuming it is measured in kelvin we take Einstein relation in the form $D = k_{\mathrm{B}} b \tau$ where k_{B} is the Boltzmann constant.

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Such a simple model however does not give a comparable value of the Planck's constant for the Schrödinger type equation unless we manipulate the factor k we want to put in the Tolman-Thorne equation Eq. (3).

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An effect of a variable k can also be produced by not assuming a linear dependence of the diffusion coefficient on temperature.

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We shall take the diffusion coefficient to be $D = i k_{\mathrm{B}} b |\tau|^{1+\alpha}$.

Schrödinger type equation

Assuming b to be real we write $D = i\widehat{D}$. Then in a geodesic normal coordinate the concentration $C(x,t)$ about a point satisfies the equation

$$\frac{\partial C}{\partial t} = \widehat{D} i \Delta_{\widehat{g}} C - v \cdot \nabla c + \widehat{D} i \Gamma O\left(|x|^2\right) C \tag{4}$$

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Estimating the mobility b

We find an estimate for the mobility using Newtonian mechanics. Let the mass of the star be M and the asymptotically defined angular momentum per unit mass be a. Since gravitational force is the only force involved assuming Pascal's law we equate the speed ωr with $|b|$ times the gravitational force mM/r^2 and use $\omega = -W/X \approx 2Ma/r^3$ for large r.

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Heuristically for a test particle of mass m, $|b| = \dfrac{2|a|}{m}$. Since for large r, $\tau = -i(|\Omega|r)^{-1} + O(r^{-2})$ we get

$$\widehat{D} \approx -\frac{2ak_{\mathrm{B}}}{m(\Omega r)^{1+\alpha}} \tag{6}$$

We take $\widehat{D} < 0$. b is negative because drag force opposes the velocity.

Planck's type constant from g-temperature

Equating $\widehat{D}$ to $-\frac{\hbar_{\mathrm{g}}}{2m}$ we then get an analogue of the reduced Planck's constant for our imaginary g-temperature:

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For numerical estimation we remove a using the radius of the star: $a \approx (2/5)R^2\Omega$. Also use $\Omega^2 \approx (4\pi/3)\epsilon_{\rm ave}$ where $\epsilon_{\rm ave}$ be the average density. Thus Eq. (7) gives

$$\hbar_{\rm g} \approx \frac{1.6R^2 k_{\rm B}}{(4\pi\epsilon_{\rm ave}/3)^{\alpha/2} r^{1+\alpha}} \approx \frac{1.6R^{2+1.5\alpha} k_{\rm B}}{M^{\alpha/2} r^{1+\alpha}} \tag{8}$$

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With $\alpha = 1$, $R = R_\odot = 6.96 \times 10^{10}$cm and

$\epsilon_{\rm ave} = \epsilon_\odot = 1.05 \times 10^{-28}$cm^{-2} we get $\hbar_{\rm g} \approx \hbar$ at $r \approx 10^{18}$cm.

r distance from the axis of symmetry.

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For a rotating stationary star the points on a $t =$ constant hypersurface where the Killing vector field K^a becomes null is a surface. Let us denote the minimum ρ-value on the intersection of this surface with the equatorial plane by ρ_i. In case this minimum value occurs at a point where the asymptotic coordinate system is a valid approximation we denote the corresponding value by r_i.

g-Planck parameter for quantum particles

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First we estimate the distance at which g-temperature becomes imaginary. If we continue to believe that this distance is of the order of Ω^{-1} and angular frequency of the neutron is related to its spin ½ by $\Omega = 2\hbar M^{-1} R^{-2}$ then this distance is approximately 0.6×10^{-4} Bohr radius.

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We estimate $\hbar_g$ for the case $\alpha = 1$. Eq. (9) gives $\hbar_g \approx \hbar$ at $r \approx 10^{-9}$cm ≈ 0.2 Bohr radius.

Consequences of variable h_g

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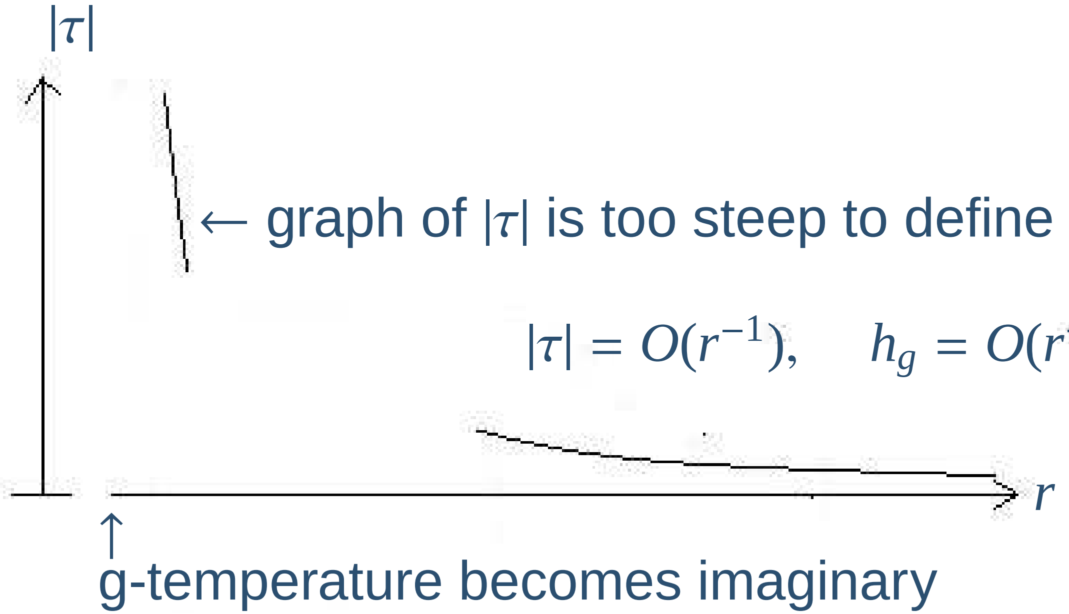
- Variable coupling “constant" would give a scalar field with EYM equations.
- Can we get stable particle-like solutions of EYM equations this way?

A rough graphical representation



$$|\tau| = O(r^{-1}), \quad h_g = O(r^{-1-\alpha})$$

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