Компактни звезди в минимална дилатонна гравитация

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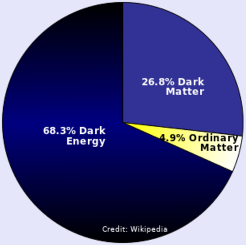
Overview

1. Защо имаме нужда от нова теория?
   - Наблюдателни тестове
   - Нерешени проблеми за компактните звезди
   - Как да разширим GR
   - Алтернативни теории на гравитацията
2. Минимална дилатонна гравитация
3. Приложение за компактни звезди
   - Неутронни звезди
   - Бели джуджета
4. Включване на уравненията в COCAL
5. Бъдещи планове

Тестове на общата относителност (GR)

General relativity has been tested on many scales, but mostly in weak to moderate-field regime:

- Laboratory, Earth and Solar System scale ($v/c << 1$ or $GM/c^2R << 1$)), upper bound for violations by the Cassini mission – 10^{-5}
- Binary pulsars: PSR B1913+16, PSR J0737-3039, PSR J0348+0432 – 0.05%
- Galaxies and galaxies cluster: Sloan Digital Sky Survey III Baryon Oscillations Spectroscopic Survey – 6%



The real probes for the strong field regime ($v/c > 0.1$ or $GM/c^2R \sim 1$) are:

- Final stages of binary coalescence of compact objects (WD, NS, BH)
- Cosmological tests of the (early) Universe

Known problems: Classical theory (not renormalizable), Singularities, Cosmological constant problem, Vacuum fluctuations, Dark Energy, Dark Matter, The initial inflation and initial singularity problem etc.

Примери за това което не знаем:

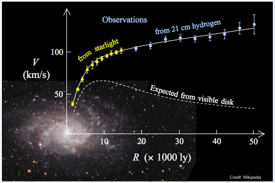
- The rotation curves of disc galaxies [Corbelli & Salucci (2000)]
- Weak gravitational lensing results [Clowe et al. (2006), Huterer (2010)]
- An ongoing quest:

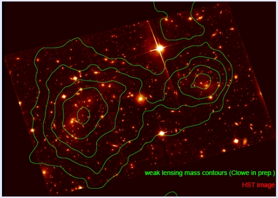
  – The Dark Energy Survey (operational),

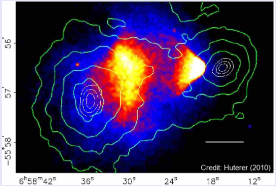
  – Sloan Digital Sky Survey III (operational, 35% of the sky, with photometric observations of around 500 million objects and spectra for more than 1 million objects),

  – The Euclid Mission (2020, L2 space telescope)

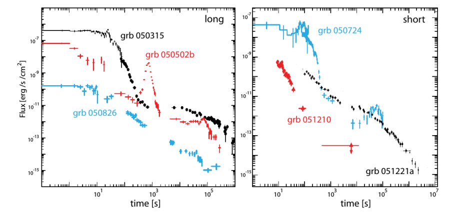
  – HETDEX (2014), DESI (2018), BOSS(operational) etc.

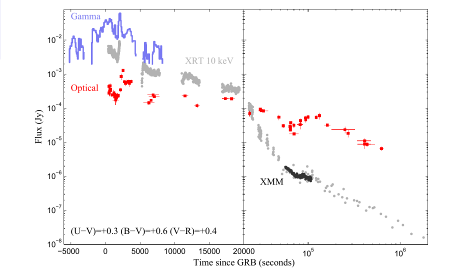






Мистериата на гама избухванията





1. Energy $\sim 10^{53} erg$, two types – Short and Long
2. Different variability time-scales – ms, sec, hundreds of seconds
3. X-ray plateaus – continued injection of energy ($\sim 100s$)
4. X-ray flares – multiple rebrightening, happening at up to $10^5 s$
5. Ultralong GRBs (GRB 091024A, GRB 111209A) – GRBs with γ-emission lasting more than 1000s (APJ, 778:54, 2013, ApJ 766:30, 2013)
6. Extended high energy emission (GeV scale, example GRB130427A)
7. All those properties call for a long-lasting, extremely powerful central engine
8. Figure credit: Gehrels et. al (2009), Gendre et al. (2012), ApJ 766, 30, 2013(GRB

Компактните звезди в GR:

White dwarfs (WD) and neutron stars (NS) – significant observational data and modelling efforts, but still inconsistencies:

- The ultra-massive white dwarfs: SNLS-03D3bb (Nature 443 (2006) 308) and SN2007if (ApJ 713 (2010)), type Ia SN with progenitor exceeding the $M_{Ch} = 1.4M_{\odot}$ (up to 2.4-2.8$M_{\odot}$)
- Stiff M(R) dependence for neutron stars or a dispersion in the observed masses?
- The question of the maximal NS mass and its relation to stellar black holes and astrophysical jets
- The Gamma-Ray Bursts mistery: huge energies, short characteristic time-scales, long life of the central engine

There are numerous approaches towards solving these problems – better MHD modeling, stronger and more complicated magnetic fields, better and richer equation of states etc.

One can also choose to go to a deeper level and extend the very GR.

Как да разширим GR

Requirements:

- reproduce the Minkowski spacetime in the absence of matter and cosmological constants,
- be constructed from only the Riemann curvature tensor and the metric,
- follow the symmetries and conservation laws of the stress-energy tensor of matter,
- reproduce Poisson's equation in the Newtonian limit.

Starting from the Einstein-Hilbert action, one can:

- increase the spacetime dimensions
- change the functional dependence of the Lagrangian density on the Ricci scalar R
- include other scalars generated from the Riemann curvature in the Lagrangian density,
- include additional scalar, vector, or tensor fields.

Алтернативни теории на гравитацията

Some of the more popular alternatives of GR ($A_E = \int \frac{1}{2\kappa} R\sqrt{-g}\,\mathrm{d}^4 x$) :

- **Gaus Bonnet theory** – includes a term of the form: $G = R^2 - 4R^{\mu\nu}R_{\mu\nu} + R^{\mu\nu\rho\sigma}R_{\mu\nu\rho\sigma}$ in the action $A = \int d^D x\sqrt{-g}\,G$. (no additional dynamical degrees of freedom)
- **Lovelock theory** – a natural generalization of GR to $D > 4$.

$$\mathcal{L} = \sqrt{-g}\,(\alpha_0 + \alpha_1 R + \alpha_2 \left(R^2 + R_{\alpha\beta\mu\nu}R^{\alpha\beta\mu\nu} - 4R_{\mu\nu}R^{\mu\nu}\right) + \alpha_3 \mathcal{O}(R^3))$$

- $f(R)$ **theories** – a familly of theories in which the arbitrary function $f(R)$ may lead to the accelerated expansion and structure formation of the Universe /dark energy or dark matter alternative/. $A = \int \frac{1}{2\kappa} f(R)\sqrt{-g}\,\mathrm{d}^4 x$
- **Brans-Dicke scalar-tensor theory** – the gravitational interaction is mediated by a scalar field ($\phi = 1/G$) – i .e. a varying G, as well as the tensor field of general relativity. Contain a tunable, dimensionless Brans-Dicke coupling constant ω. $A = \int d^4 x\sqrt{-g}\,\left(\frac{\phi R - \omega\frac{\partial_a \phi \partial^a \phi}{\phi}}{16\pi} + \mathcal{L}_{\mathrm{M}}\right)$
- **Chameleon scalar-tensor theory** – Introduces a scalar particle (the chameleon) which couples to matter, with a variable effective mass, an increasing function of the ambient energy density $m_{eff} \sim \rho^\alpha$, where $\alpha \simeq 1$. ($m_{eff} \sim mm - pc$).

Минимална Дилатонна Гравитация (MDG)

The action, following Fiziev, PRD **87**, 044053 (2013)

$$A_{g,\phi} = \frac{c}{2\kappa} \int d^4x \sqrt{|g|} (\Phi R - 2\Lambda U(\Phi))$$

Here, $\Phi \in (0, \infty)$ is the new scalar field called "dilaton", $\Lambda > 0$ is the cosmological constant and $\kappa = 8\pi G_N / c^2$ is the Einstein constant.

Effects

Clearly, the introduction of the scalar **dilaton** Φ leads to varying gravitational constant $G(\Phi) = G_N / \Phi$, while the introduction of the cosmological potential $U(\Phi)$ leads to a variable cosmoloical factor instead of a constant Λ.

Note: In order to keep gravity as existing and attractive force $\Phi > 0$.

Минимална Дилатонна Гравитация (продължение)

The action

$$A_{g,\phi} = \frac{c}{2\kappa}\int d^4x\sqrt{|g|}(\Phi R - 2\Lambda U(\Phi))$$

This action corresponds to the Brans-Dicke theory with $\omega = 0$.
GR is recovered for $\Phi = 1, U(1) = 1$.

In general, the MDG model and the $f(R)$ models are equivalent only locally. Only under additional conditions, the two models can be considered globally equivalent. Those conditions define the class of the potentials $U(\Phi)$, for which one also avoids some of the well-known problems in the $f(R)$ theories, like physically unacceptable singularities, ghosts, etc. .

Some of the properties of the MDG model already demonstrated:

1. The inflation and the graceful exit to the present day accelerating de Sitter expansion of the Universe ($U(\Phi)$ can be reconstructed from $a(t)$).
2. Avoids any conflicts with the existing solar system and laboratory gravitational experiments when $m_\Phi \sim 10^{-3} eV/c^2$.
3. The time of inflation as a reciprocal quantity to the mass of dilaton m_Φ.

Полевите уравнения на MDG

– variation of the MDG action with respect to Φ gives:

$$R = 2\Lambda U_{,\Phi}(\Phi) \tag{1}$$

Note: this is an algebraic relation. It ensures that Φ has the same properties as R. (for example, $R = const$ leads to $\Phi = const$ and $G(\Phi) = const$.
– variation of the MDG action with respect to $g_{\alpha\beta}$ gives:

$$\Phi G_{\alpha\beta} + \Lambda U(\Phi) g_{\alpha\beta} + \nabla_\alpha \nabla_\beta \Phi - g_{\alpha\beta} \Box \Phi = 0 \tag{2}$$

– the trace of eq. 2 leads to:

$$\Box \Phi + \Lambda V_{,\Phi}(\Phi) = 0 \tag{3}$$

Here $V_{,\Phi}(\Phi) = 2/3(\Phi U_{,\Phi}(\Phi) - 2U(\Phi))$ or $V(\Phi) = \frac{2}{3}\int_1^\Phi (\Phi U_{,\Phi}(\Phi) - 2U) d\Phi$
– And the traceless part:

$$\Phi \hat{R}_\alpha^\beta = -\widehat{\nabla_\alpha \nabla^\beta} \Phi \tag{4}$$

Крайният вид на полевите уравнения:

If we include the standard action of the matter fields Ψ, based on the minimal interaction with gravity:

$$A_{matt} = \frac{1}{c}\int d^4x\sqrt{|g|}L_{matt}(\Psi, \nabla\Psi; g_{\alpha\beta}) \tag{5}$$

we get the final form of the field equations in cosmological units $\Lambda = 1, \kappa = 1, c = 1$:

$$\begin{aligned} &\Box\Phi + 2/3(\Phi U_{,\Phi}(\Phi) - 2U(\Phi)) = \frac{1}{3}T \\ &\Phi \hat{R_\alpha^\beta} = -\widehat{\nabla_\alpha\nabla^\beta}\Phi - \hat{T_\alpha^\beta} \end{aligned} \tag{6}$$

Note: The dilaton Φ does not interact directly with the matter and thus it is a good candidate for the dark matter. Its interaction with the usual matter goes only trough the gravitational interaction.

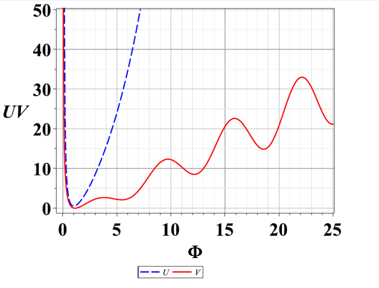
Някои свойства

1. MDG and f(R) theories are related by the Legendre transform (i.e. there is a dictionary between the two models).
2. The witholding property: In order to guarantee that $\Phi \in (0, \infty)$, we require that $V(0) = V(\infty) = +\infty$, i.e. infinite potential barriers at the end of the interval.
3. From $U(\Phi) = \frac{3}{2}\Phi^2 \int_1^{\Phi} \Phi^{-3} V_{,\Phi} d\Phi + \Phi^2$ (from $U(1) = 1$), if we assume that $V(\Phi) \sim v\Phi^n$, it follows that $U(0) = U(\infty) = +\infty$.
4. Additional requirement: $U(\Phi) > 0$, for $\Phi \in (0, \infty)$ (the cosmological term needs to have a definite positive sign).
5. From the convex condition $U_{,\Phi\Phi} > 0$, for $\Phi \in (0, \infty)$ (ensures the uniqueness of the Einstein vacuum).
6. The uniqueness of the deSitter vacuum is not guaranteed:

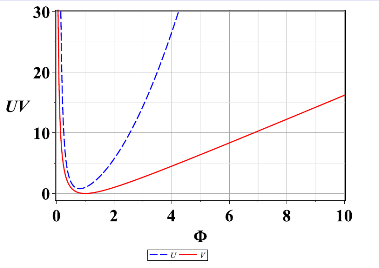
$$V_{,\Phi\Phi} = \frac{2}{3}(\Phi U_{,\Phi\Phi} - U_{,\Phi}), V_{,\Phi\Phi\Phi} = \frac{2}{3}\Phi U_{,\Phi\Phi\Phi}$$

Thus we can have $V(\Phi)$ with several minima in the domain.

Credit: Fiziev, Physical Review D 87, 044053 (2013)



(д) Unique Einstein Vacuum and many deSitter vacuums: $U_{,\Phi\Phi} > 0$



(e) Unique Einstein Vacuum and unique deSitter vacuums: $U_{,\Phi\Phi} > 0$, $V_{,\Phi\Phi} > 0$

Пример за МДГ с единствен dSV

If we postulate a unique deSitter vacuum, then the function $V(\Phi)$ will be convex for $\Phi \in (0, \infty)$ and the function $\frac{2}{3}(\Phi U_{,\Phi\Phi} - U_{,\Phi}) > 0$ is strictly positive.
A simple example of such pair of withholding potentials is:

$$V(\Phi) = \frac{1}{2} p^{-2}(\Phi + 1/\Phi - 2) \tag{7}$$

$$U(\Phi) = \Phi^2 + \frac{3}{16} p^{-2}(\Phi - 1/\Phi)^2 \tag{8}$$

where p is a small parameter related with the dilaton mass.

We are going to use these witholding potentials in our study of compact stars.

Some of the works where details on the MDG model have been worked out.

A theory in development

Fiziev, arXiv:1402.2813 [gr-qc], "Frontiers of Fundamental Physics 14 Marseille, France, July, 15-18, 2014, PoS(FFP14)080
P.P. Fiziev, Physical Review D 87, 044053 (2013)
P. Fiziev, Georgieva D., Phys. Rev. D 67 064016 (2003).
Plamen P. Fiziev, arXiv:gr-qc/0202074
Fiziev P. P., Yazadjiev S., Boyadjiev T., Todorov M., Phys. Rev. D 61 124018 (2000).
P. P. Fiziev, Mod. Phys. Lett. A, 15 1077 (2000)

The pioneering work on the MDG model is by O'Hanlon, Phys. Rev. Lett. 29 137 (1972).

Приложение за компактни звезди

We follow the first application to the case of neutron stars published in [Fiziev (2013)]:
Let us consider a static, spherically symmetric metric of the type:
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$$ds^2 = e^{\nu(r)}dt^2 - e^{\lambda(r)}dr^2 - r^2 d\Omega^2, \tag{9}$$

where r is the luminosity distance to the center of symmetry, and $d\Omega^2$ describes the space-interval on the unit sphere.
The equations are the MDG field equations:

$$\begin{aligned} &\Box\Phi + 2/3(\Phi U_{,\Phi}(\Phi) - 2U(\Phi)) = \frac{1}{3}T \\ &\Phi \hat{R_\alpha^\beta} = -\widehat{\nabla_\alpha \nabla^\beta}\Phi - \hat{T_\alpha^\beta} \end{aligned} \tag{10}$$

Then, if we assume the perfect fluid stress-energy tensor $T^{\mu\nu} = diag(\epsilon, p, p, p)$ $/c = 1/$ we obtain:

1. For the inner domain $r \in [0, r_*]$:

$$\frac{dm}{dr} = 4\pi r^2 \epsilon_{eff}/\Phi \qquad (11)$$

$$\frac{dp}{dr} = -\frac{p+\epsilon}{r}\frac{m + 4\pi r^3 p_{eff}/\Phi}{\Delta - 2\pi r^3 p_\Phi/\Phi} \qquad (12)$$

$$\frac{d\Phi}{dr} = -4\pi r^2 p_{eff}/\Delta \qquad (13)$$

$$\frac{dp_\Phi}{dr} = -\frac{p_\Phi}{r\Delta}\left(3r - 7m - \frac{2}{3}\Lambda r^3 + 4\pi r^3 \epsilon_{eff}/\Phi\right) - \frac{2}{r}\epsilon_\Phi \qquad (14)$$

Additionally, we have:

$$\epsilon_\Lambda = -p_\Lambda - \frac{\Lambda}{12\pi}\Phi,$$

$$\epsilon_\Phi = p - \frac{1}{3}\epsilon + \frac{\Lambda}{8\pi}V'(\Phi) + \frac{p_\Phi}{2}\Pi$$

$$\epsilon = \epsilon(p)$$

where

$\Delta = r - 2m - \frac{1}{3}\Lambda r^3$, $\epsilon_{eff} = \epsilon + \epsilon_\Phi + \epsilon_\Lambda$, $p_{eff} = p + p_\Phi + p_\Lambda$, $\Pi = \frac{m + 4\pi r^3 p_{eff}/\Phi}{\Delta - 2\pi r^3 p_\Phi/\Phi}$

and

$\epsilon_\Lambda = \frac{\Lambda}{8\pi}(U(\Phi) - \Phi)$, $p_\Lambda = \frac{\Lambda}{8\pi}(U(\Phi) - \frac{1}{3}\Phi)$

...

The 4 unknown functions are $m(r), p(r), \Phi(r), p_\Phi(r)$.

Начални и гранични условия:

$$m(0) = m_c = 0, \Phi(0) = \Phi_c, p(0) = p_c$$

$$p_\Phi(0) = p_{\Phi c} = \frac{2}{3}\left(\frac{\epsilon(p)}{3} - p_c\right) - \frac{\Lambda}{12\pi} V'(\Phi_c)$$

On the star's edge ($p(r^*) = 0$) we have

$$m^* = m(r^*; p_c, \Phi_c), \Phi^* = \Phi(r^*, p_c, \Phi_c), p^*_\Phi = p_{\Phi c}(r^*, p_c, \Phi_c)$$

2. For the outer domain: a boundary value problem for Φ:

$$p = 0, \epsilon = 0, \Phi_\Delta = 1$$

After introducing the EOS, we solve the ODE system + the initial and boundary conditions for the unknown functions $m(r), p(r), \Phi(r), p_\Phi(r)$.

Случаят на TOV неутронна звезда

If one uses the Tolman-Oppenheimer-Volkov (TOV) model for EOS (ideal Fermi neutron gas at zero temperature):

$M = 1.4 - 2M_{\odot}$
$R = 12 - 13km$
$\rho = 10^9 - 10^{17} kg/m^3$
Composition: $n^0(...)$

$$\epsilon = \frac{1}{4\pi}K(\sinh(t) - t), p = \frac{1}{12\pi}K(\sinh(t) - 8\sinh(t/2) + 3t)$$

Here $K = \pi\frac{m^4c^5}{4h^2}$, $t = 4log\left(\frac{p_F}{mc} + \left(1 + \left(\frac{p_F}{mc}^2\right)\right)^{1/2}\right)$ and

$p = \sqrt{\Lambda}\hbar/cm_{\Phi} = 10^{-21}$ (the dilaton mass parameter, for observational consistency, $p < 10^{-30}$), $\Lambda \sim 10^{-44}km^{-2}$,
EOS in the original notations of [Oppenheimer & Volkoff (1939)], see also [Rezzola & Zanotti (2013)].
We use MAPLE to solve the ODE system using the shooting method for the BC and the rosenbrock method for the integration.

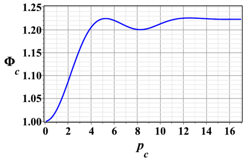


FIG. 1: The specific MDG-curve $F_\Lambda(p_c, \Phi_c) = 0$

(ж)

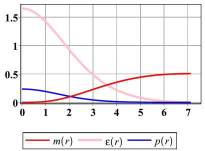


FIG. 2: The MDG-SSSS interior in accord with MEOS

(з)

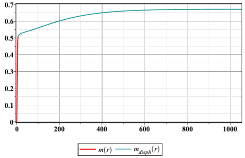


FIG. 3: The SSSS-disphere-mass-dependence on r

(и)

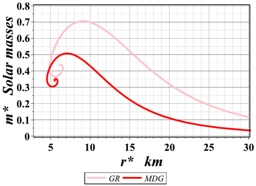


FIG. 7: Mass - radius relations for IFNG0T in GR ($m^*_{max} \approx .7051\, m_\odot$, $r^*_{max} \approx 9.209$ km) and in MDG ($m^*_{max} \approx .5073\, m_\odot$, $r^*_{max} \approx 7.092$ km)

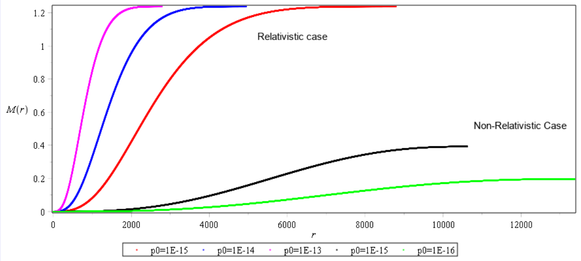
(к)

TOV уравнения за бели джуджета

In the case of GR, the white dwarfs are described well even in the polytropic approximation:

$M_{WD} = 0.17 - 1.3 M_{\odot}$
$R_{WD} = 0.008 - 0.02 R_{\odot}$
$\rho_{WD} = 10^5 - 10^9 gr/cm^3$
Composition:
He, C, O
The ODE system:

$$\frac{dM(r)}{dr} = \beta r^2 \epsilon$$
$$\frac{dp(r)}{dr} = \frac{\alpha \epsilon M(r)}{r^2}$$
$$\epsilon = (p(r)/K)^{1/\nu}$$



Here the integration has been performed using Maple. /M(r) is in $M_{\odot}$, r in [km]/

Бели джуджета в MDG (за $A/Z = 2.15$)

In the case of white dwarfs, we use the polytropic EOS in the two regimes – the relativistic case ($k_F >> m_e$) and the non-relativistic case $k_F << m_e$:

$$p_{nonrel} = K_{nonrel}\epsilon^{\frac{5}{3}}, p_{rel} = K_{rel}\epsilon^{\frac{4}{3}},$$

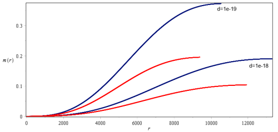
where

$$K_{nonrel} = \frac{\hbar^2}{15\pi^2 m_e}\left(\frac{3\pi^2 Z}{A m_N c^2}\right)^{5/3}, K_{rel} = \frac{\hbar c}{12\pi^2}\left(\frac{3\pi^2 Z}{A m_N c^2}\right)^{\frac{4}{3}}$$

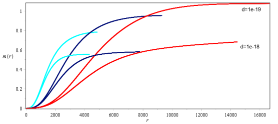
We make the equation dimensional following [Sibar and Reddy (2004)].

Model	r_{MDG}	m_{MDG}	r_{GR}	m_{GR}
Relativistic WD ($p0 = 10^{-14}$)	4 947	1.2406	4840	1.2431
Relativistic WD ($p0 = 10^{-15}$)	8 799	1.2419	8600	1.2432
Relativistic WD ($p0 = 10^{-16}$)	15 648	1.2427	15 080	1.2430
Non-Relativistic ($p0 = 10^{-15}$)	10 603	0.3929	10 620	0.3941
Non-Relativistic ($p0 = 10^{-16}$)	13 349	0.1969	13 360	0.1974

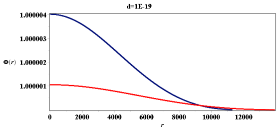
Бели джуджета в МДГ (M в слънчеви маси, r в km, p в $ergs/cm^3 * 10^{38}$)



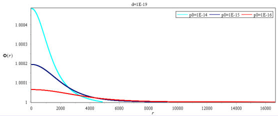
(м) Non-relativistic case



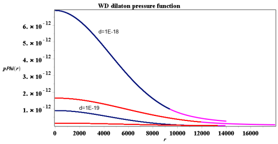
(н) Relativistic case



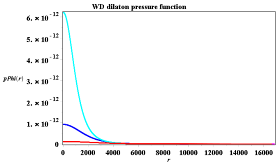
(о) Non-relativistic case



(п) Relativistic case

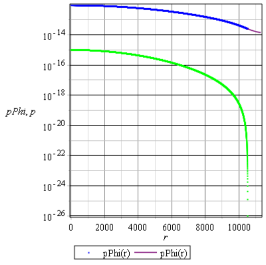


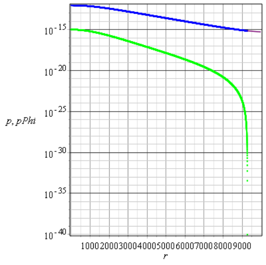
(р) Non-relativistic case

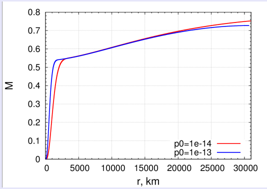


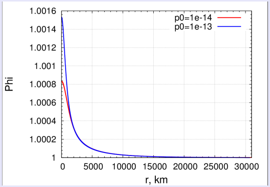
(с) Relativistic case

Двете безразмерни налягания и малко забавления с метода на Rosenbrock във FORTRAN









Резултатите на кратко

1. Уравненията в МДГ възстановяват GR с добра точност ($\Phi = 1, U(1) = 1, \Lambda = 0$)
2. За масивен дилатон, кривите на $M(R)$ са подобни на тези в GR
3. В случая на неутронни звезди, общата маса е 30% от тази на НЗ
4. За бели джуджета, масата на диласферата е около $\sim 27\%$ от тази на звездата
5. Масата на белите джуджета расте с включването на масивен дилатон
6. Достигнатата маса за дилатона към момента е ($d \sim 10^{-20}$), което е доста над нужното $\sim 10^{-30}$.

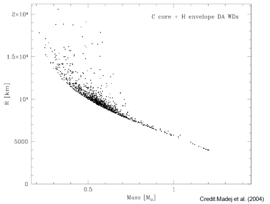


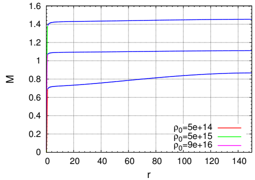
Fig. 2. Mass – radius relation for 1175 hot white dwarfs of the same sample. The relation does not extend to masses M higher than $1.2\,M_\odot$, or rather to the highest surface gravities $\log g > 9.0$.

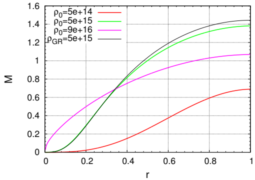
Резултатите в случаите на тези просто уравнения на състоянията са обещаващи, но са нужни нови кодове, за да се решат уравненията за много лек дилатон!

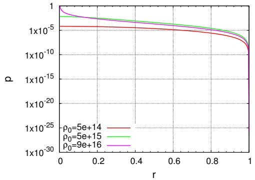
Включването на уравненията в COCAL, с Antonios Tsokaros, ITP

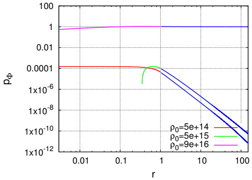
As part of my COST visit at the ITP, the MDG static equations were implemented in the Compact Object CALculator (Tsokaros et al. in prep (2014)).

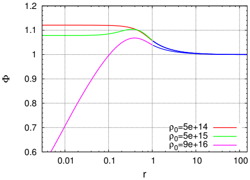
Some preliminary results for the NS case /here $\gamma = 2$/:





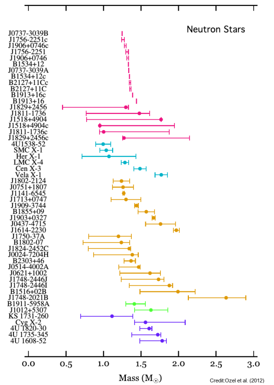






Какво остава да бъде направено?

1. Да се изпозлват по-реалистични EOS за случаите на WD и NS (например използвайки бази данни като cococubed)
2. Да се приближим до космологичния хоризонт
3. Да използваме Cocal (с Antonios Tsokaros)
4. $3 + 1$ формулировка на полевите уравнения
5. Да се използва COCAL за въртящи се неутронни звезди
6. А може би дори и за двойни системи



Крайната цел е да се получат масивни звезди в МДГ без нуждата от сложни уравнения на състоянието, или поне да се преразгледа зависимостта $M(R)$.

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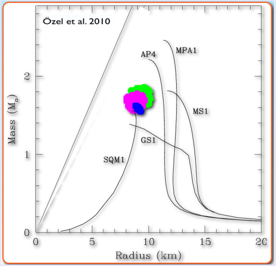

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Това е!

Благодаря за вниманието!

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