III. Semester report

by **Máté Pszota** (pszota.mate@wigner.hun-ren.hu)
PhD Program: Astronomy and Space Physics
Supervisor: **Péter Ván**[1]
Ph.D. Thesis title: Consequences of thermodynamic constraints in the classical theory of gravitation
(Termodinamikai kényszerek következményei a klasszikus gravitációelméletben)

2024/2025 I. semester

[1]HUN-REN Wigner RCP

Introduction

My planned research applies extensions of modern continuum theories to produce astrophysically relevant predictions. In the investigated theory [1], the second law of thermodynamics is used as a constraint in a nonequilibrium framework. The derived evolution equation with an introduced scalar field yields Poisson's equation of Newtonian gravity, or in an extended version, its modified form. The extension results in nonlinear field equation, which is tested against astrophysical phenomena, specifically against galactic rotation curves. This method allows the explanation of some dark matter-related phenomena without introducing exotic, new matter or particles. Modified gravity has been researched for decades to explain cosmological phenomena and issues with the dark matter model, but in my research, a novel and unique approach is tested. Furthermore, its potential applications for the explanation of non-galactic phenomena is considered an open issue, which warrants further research.

Description of research work carried out in current semester

In this semester, I further investigated the potential Solar system-level predictions of thermodynamic gravity, by calculating the difference between the Newtonian and TG predictions of the perihelion precession of Mercury and light bending around the Sun. For the latter, in the simple Newtonian model, an analytical solution for the angular deflection Θ of a light particle as it travels near a star with mass M, approaching it at a distance of R at the closest point:

$$\Theta_{Newtonian} = \frac{2GM}{c^2R}, \tag{1}$$

$$\Theta_{TG} = \frac{2GM}{c^2R}\cdot\frac{R}{KGM}\cdot\left[\frac{\pi}{2}\left(1-\frac{R}{\sqrt{R^2-G^2M^2K^2}}\right)+\frac{R}{\sqrt{R^2-G^2M^2K^2}}\cdot\arctan\left(\frac{GMK}{\sqrt{R^2-G^2M^2K^2}}\right)\right]. \tag{2}$$

An important research avenue this semester was the incorporation and comparison of the self-consistent gravity approach with TG. Self-consistent gravity [2] accounts for the relativistic effect of the gravitational field's energy being equivalent with mass, per SR, and produces a modified Poisson's equation to account for this:

$$\Delta\varphi = \frac{4\pi G}{c^2}\rho\varphi + \frac{1}{2\varphi}(\nabla\varphi)^2. \tag{3}$$

By using a general function for thermodynamic gravity with heuristic approach to derive TG, we can use a different self-energy term instead of the one in the usual derivation. Thus, from the general initial equation of

$$u = e - \varphi - \frac{\Sigma(\varphi,\nabla\varphi)}{\rho}, \tag{4}$$

we can obtain in the case of $\Sigma(\varphi,\nabla\varphi) = \frac{c^2}{8\pi G\varphi}(\nabla\varphi)^2$ (to account for the effects of the self-consistent corrections):

$$\Delta\varphi = \frac{1}{2}\left(\frac{1}{\varphi}+2K\right)(\nabla\varphi)^2 + \frac{4\pi G}{c^2}\rho\varphi, \tag{5}$$

as is Eq. 22 in [2] in the $K = 0$ limit. By writing the equation with $\sqrt{\varphi}$, we can get the following form:

$$\Delta(\sqrt{\varphi}) = \frac{2\pi G}{c^2}\rho\sqrt{\varphi} + 2K\sqrt{\varphi}\left(\nabla\left(\sqrt{\varphi}\right)\right)^2. \tag{6}$$

In the case of vacuum ($\rho(r) = 0$), the solution is

$$\varphi(r) = -\frac{1}{K}\mathrm{erf}^{-1}\left(-\sqrt{-\frac{K}{c^2\pi}}\left(2c^2 - \frac{GM}{r}\right)\right)^2. \tag{7}$$

I implemented a numerical solution to solve the case of a constant-density region conjoined to an outer vacuum (Fig. 1):

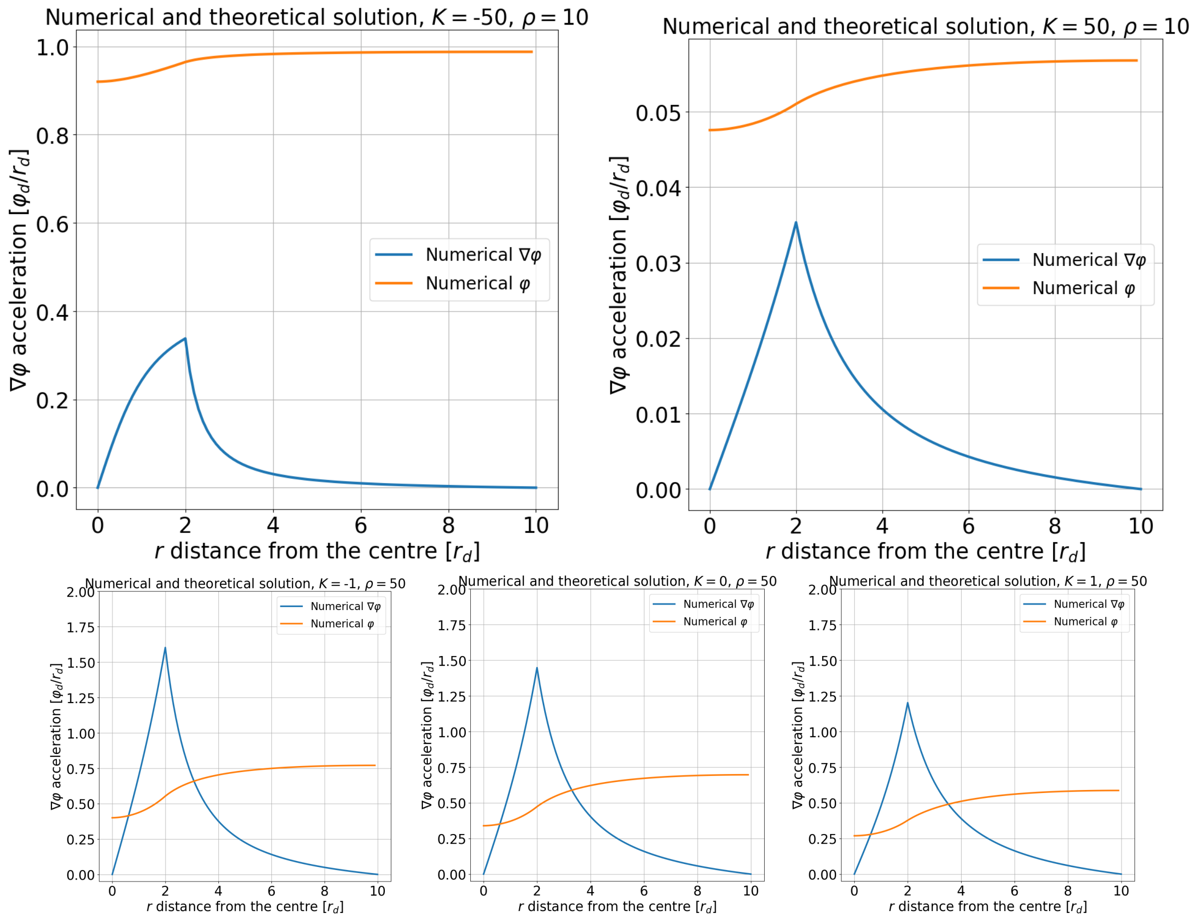

Figure 1: The result of the numerical method compared to the theoretical solutions with various K and ρ values. Constant density up to $r = 2r_d$, then vacuum. Boundary conditions $\nabla\varphi(0) = \nabla\varphi(10r_d) = 0$.

I also calculated the potential effects of including the cross-effect coupling term from TG within the method described in [2], which resulted in the following form of modified Poisson's equation:

$$\Delta\varphi = K(\nabla\varphi)^2 \frac{1/2 - e^{K\varphi}}{1 - e^{K\varphi}}, \tag{8}$$

but solutions consistent with the usual self-consistent results in the $K = 0$ limit require further research.

A research avenue to produce fits for the rest of the SPARC sample is planned via the traditional TG method with the potential inclusion of insights from self-consistent gravitational solutions. Fitting the inclinations and distances of the galaxies may produce better results, and if a large enough sample is investigated, Bayesian analysis could provide a potential way to compare the model's success with other, more developed mainstream models.

Publications

- Published article:

  M. Pszota and P. Ván. *Field equation of thermodynamic gravity and galactic rotational curves.* Physics of the Dark Universe, 46:101660, 2024.

Studies in current semester

- (Exo)Planetary atmospheres seminar I. ((Exo)Bolygólégkörök szeminárium I.,) (FIZ/5/043)

  During this course, we presented topics from the book Exoplanetary Atmospheres by Kevin Heng. The course covered topics from the observation of exoplanetary atmosphere through the description of radiative transfer to spectral lines. I presented the topics about the introduction to radiative transfer and spectroscopic line lists.

- Chapters from modern astronomy and cosmology (Fejezetek a modern csillagászatból és kozmológiából) (FIZ/5/017)

  During this course, we learned about the radiative processes in astrophysics. The topics include thermal and non-thermal radiative processes, and the propagation of radiation in astrophysical media. The course also includes a semester-ending project work, which contains various theoretical and practical problems to investigate and solve.

Conferences in current semester

- Oral presentation at the International Conference on Thermodynamics 2.0 (online) with the title *Gravity in non-equilibrium Thermodynamics*, Appalachian State University, Boone, USA, August 05-07, 2024, (`https://iaisae.org/index.php/agenda-schedule-t2022/`).

- Oral presentation at Time Machine Factory [unspeakable, speakable] on Time Travel - 2024 with the title *Gravity and nonequilibrium thermodynamics: the origin of evolution equations*, Turin, Italy, September 22-25, 2024, (`https://indico.ict.inaf.it/event/751/overview`).

- Oral presentation at Simonyi-Nap 2024 with the title *A sötét Univerzum - a gravitáció módosítása a kulcs az évtizedes rejtélyhez?*, Budapest, Hungary, October 10th, 2024, (`https://wigner.hu/hu/simonyi-nap-2024-0`).

- Oral presentation at Statisztikus Fizikai Nap 2024 with the title *Termodinamika, gravitáció és asztrofizikai alkalmazása*, Budapest, Hungary, October 25th, 2024, (`https://sites.google.com/view/statfiznap24/`).

- Poster presentation at Zimányi School Winter Workshop 2024 with the title *Galactic rotation curves with thermodynamic gravity*, Budapest, Hungary, December 02-06, 2024, (`https://zimanyischool.kfki.hu/24/`).

Further activities

Teaching activity in current semester

I participated in teaching the Classical Physics Laboratory (laboratory practice), for 8x4 hours (once per week 4 hours, for a total of 32 hours).

Science communication

I participated in the organisation of the Náboj physics contest for secondary school students on 15th November 2024 and in the Night of Researchers demonstrations at the ELTE and HUN-REN Wigner RCP on 27th September 2024.

References

[1] Peter Ván and Sumiyoshi Abe. Emergence of extended Newtonian gravity from thermodynamics. *Physica A: Statistical Mechanics and its Applications*, 588:126505, 2022.

[2] J. Franklin. Self-consistent, self-coupled scalar gravity. *American Journal of Physics*, 83(4):332–337, 04 2015.