Máté Pszota[1,2,3]

Peter Ván[2,3,4]

Galactic rotation curves with thermodynamic gravity

[1] *Eötvös Loránd University, Institute of Physics, Budapest, Hungary*

[2] *HUN-REN Wigner Research Centre for Physics, Inst. Part. Nucl. Phys., Budapest*

[3] *BME Dept. Energy Eng., Budapest*

[4] *Montavid Thermodyn. Res. Gr., Budapest*

pszota.mate@wigner.hun-ren.hu, van.peter@wigner.hun-ren.hu

Abstract

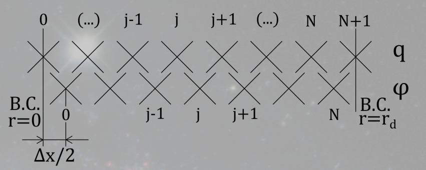
The application of a theory of thermodynamic gravity is presented, which is derived in the framework of non-equilibrium thermodynamics with weakly nonlocal internal variables in [1]. The resulting nondissipative gravitational field in eq. 2 differs resulting in modified gravity. Analytical solutions show a double crossover, allowing for different gravitational behaviour on different size scales [2]. This effect is considered a possible explanation for the source of dark matter-related effects on the galactic scale while allowing different dynamics on the extragalactic scales. The analysis for three galaxies from the Spitzer Photometry and Accurate Rotation Curves (SPARC) sample is presented with observational data as the source for the density distribution.

Numerical solution

A numerical method was developed using the following dimensionless dissipative form of eq. 2:

$$\partial_t \varphi = \Delta\varphi - \tilde{K}\left(\nabla\varphi\right)^2 - \rho(r). \qquad (1)$$

The schematic representation of the discretisation method of staggered grids, where the boundary conditions (B.C.) are set for the derivative field ($q = \nabla\varphi$) using the observed velocity data.

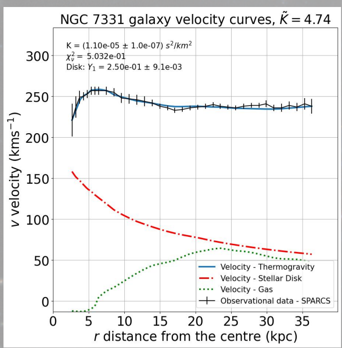


Conclusions

In this work, we have shown how a generalisation of Newtonian gravity emerges from nonequilibrium thermodynamics and the field equation of thermodynamic modified gravity reproduces the velocity curves of galaxies NGC 3198, NGC 7331 and NGC 7793 from the SPARC sample, fitting the K parameter and M/L ratio. A comparison with the dark matter model used in [5] and MOND EFE fit in [3] is also presented for the galaxy NGC 3198.

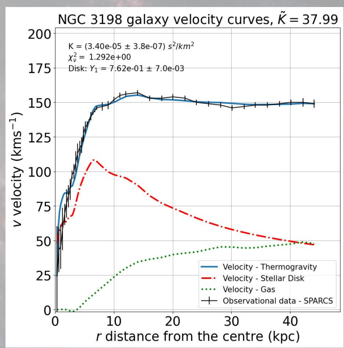
The connection between thermodynamics and gravity emerged from the thermodynamic properties of black holes, and some generalisations of general relativity can be substantiated with nonequilibrium thermodynamics.

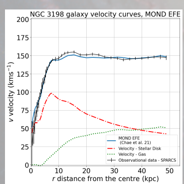
NGC 7331

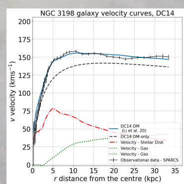


The galactic disk contribution (in red) is measured through its luminosity, then is scaled by a fitted mass/luminosity ratio (Υ_1) relative to the SPARC dataset. The contributing gas (in green) is unchanged from the presented velocity contribution, which includes hydrogen and accounts for the effect of cosmological helium.

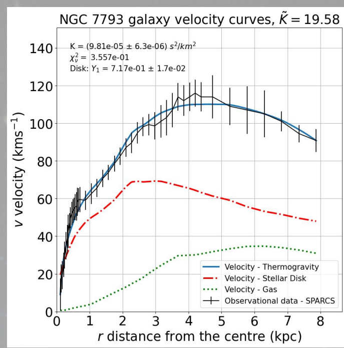
NGC 3198







NGC 7793



The distance and the inclination of galaxies is usually also a fitted parameter, but in our case thermodynamic gravity produced a good fit for these galaxies without changing the original values. Unlike the usual method of directly fitting via a MCMC algorithm to a parametrised velocity function, we used the least-squares method.

Galactic velocity curves

Using the observed densities and velocity data from the SPARC sample [6] allows us to test the predictions of the theory. We compared the numerical solution with the fitted DC14 (from Di Cintio et al. 2014) dark matter halo model of [5] and with the External Field Effect realisation of Modified Newtonian Dynamics (MOND-EFE) from [3].

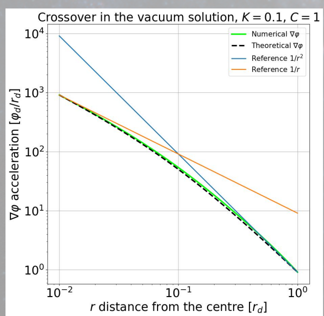
Thermodynamic gravity gives the following field equation with certain assumptions [1]:

$$\Delta\varphi = 4\pi G\rho + K(\nabla\varphi)^2, \qquad (2)$$

where φ is the gravitational potential, ρ is the mass density, G is the Newtonian constant of gravitation, and K is a material constant, with $K = 0$ returning Newtonian gravity. The exact vacuum solution of this equation is the following:

$$\varphi(r) = -\frac{1}{K}\ln\frac{r}{K + Cr} + \varphi_0. \qquad (3)$$

In the Newtonian limit, $C = 1/GM$. A comparative benchmark for the theory is the rotational star velocity distribution of galaxy halos [4], where baryonic matter alone cannot explain the observations.



The above figure shows a double crossover in the analytical solution (from eq. 3, the black dashed line) and numerical realisation (green line) of eq. 2 with a fixed inner boundary and vacuum above. The solution approaches the asymptotics $1/r$ (red) and $1/r^2$ (blue) at different distances [2].

Theory

Numerical solution

References

[1] P. Ván, S. Abe. Emergence of modified Newtonian gravity from thermodynamics, *Physica A*, 588:126505, 2022.

[2] S. Abe, P. Ván, Crossover in extended Newtonian gravity emerging from thermodynamics *Symmetry*, 14:1048(7), 2022.

[3] K.-H. Chae, H. Desmond, F. Lelli, S.S. McGaugh, J.M. Schombert *The Astrophysical Journal*, 921(2):104, 2021

[4] V. C. Rubin, J. Ford, W. Kent. *Astrophysical Journal*, 159:379,1970.

[5] P. Li, F. Lelli, S.S. McGaugh, J. Schombert *The Astrophysical Journal Supplement Series*, 247(1):31, 2020.

[6] F. Lelli, S.S. McGaugh, J.M. Schombert, *The Astronomical Journal*, 152(6):154, 2016.

We thank S. Abe and R. Trasarti-Battistoni for providing insightful remarks regarding the theory.

The work was supported by the grants National Research, Development and Innovation Office – FK134277. The research is part of project no. BME-NVA-02, implemented with the support provided by the Ministry of Innovation and Technology of Hungary from the National Research, Development and Innovation Fund, under the TKP2021 funding scheme.