Atmospheres of Eddington-luminosity relativistic stars

M. Wielgus[1,*], A. Sądowski[2], W. Kluźniak[1], M. Abramowicz[1], R. Narayan[3]

[1] Nicolaus Copernicus Astronomical Centre, ul. Bartycka 18, 00-716, Warszawa, Poland
[2] MIT Kavli Institute for Astrophysics and Space Research 77 Massachusetts Ave, Cambridge, MA 02139, USA
[3] Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02134, USA

*** maciek.wielgus@gmail.com**

Abstract

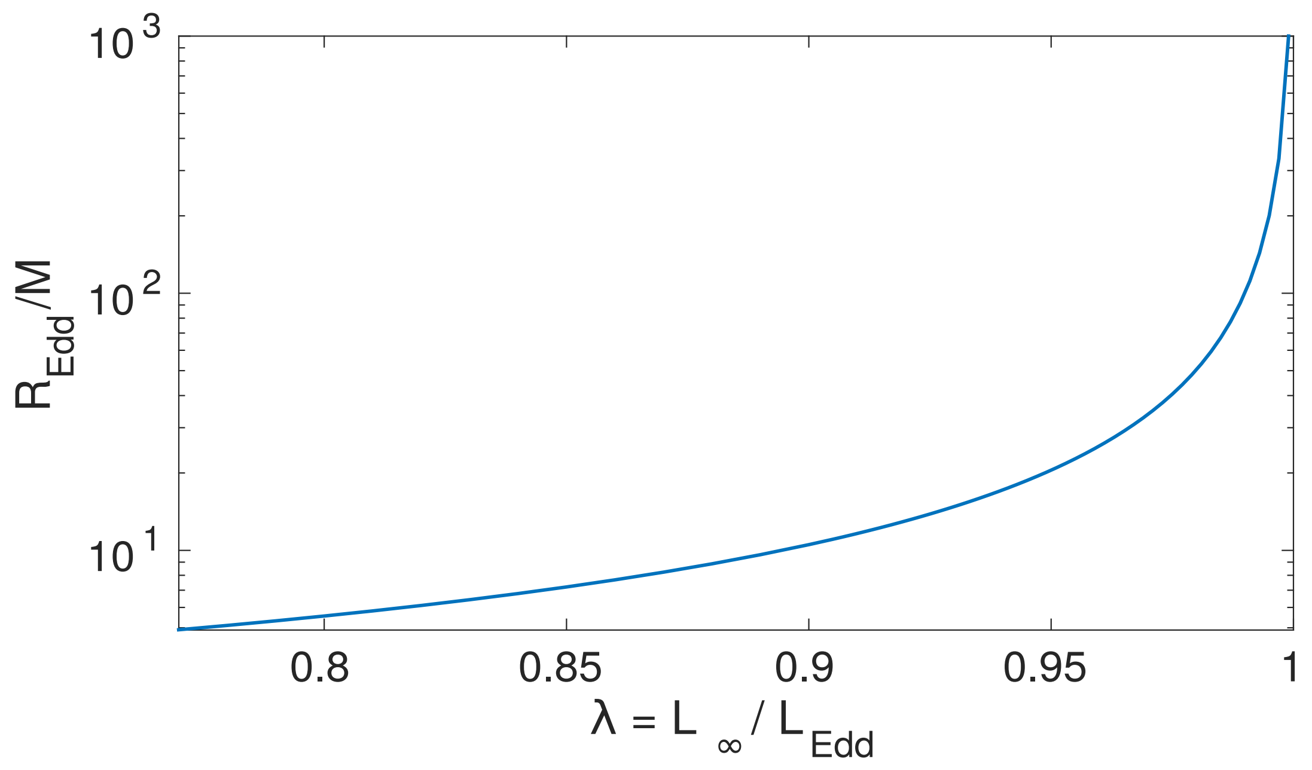
In General Relativity gaseous atmospheres may be in hydrostatic balance in the absence of a supporting stellar surface, provided that the luminosity is close to the Eddington value. We construct models of spherically symmetric shells supported by the radiation pressure of a luminous central body in the Schwarzschild metric.

Test particle equilibrium

In Newton's theory both radiation intensity and gravitation force of a luminuous spherically symmetric star diminish with square of the distance. Hence, static balance can be established for all radii, for the **Eddington luminosity**. This is not true in Schwarzschild spacetime, where for constant luminosity test particle balance is established for a particular radius,

$$R_{\mathrm{Edd}} = \frac{2GM/c^2}{1-(L_\infty/L_{\mathrm{Edd}})^2}$$

Test particles will levitate on a spherical surface at this radius, the **Eddington Capture Sphere (ECS)** [1,2], remaining static as long as the radiation flux remains unchanged. In this poster we exhibit solutions for gaseous atmospheres in hydrostatic equilibrium which are approximately centered on the ECS.



Equations

We solve the equations of **relativistic hydrodynamics** under simplyfying assumptions of spherical symmetry, looking for solutions representing atmospheres in a **static balance**. These reduce to system of two differential equations, for gas and radiation components of the total stress-energy tensor, coupled by the radiation term G_r.

We account for free-free and bound-free absorption and model electron scattering in an isotropic approximation to Klein-Nishina scattering [3]. **Local Thermodynamic Equilibrium** approximation is adopted, i.e., local energy density $R^t{}_t$ is related to temperature by the blackbody law.

The system of equations is closed with the **M1 closure scheme** [4], allowing to compute a solution of the system for a nonisotropic radiation field.

$$\begin{cases} \dfrac{dp}{dr} = \dfrac{-(\rho+p+\epsilon)M}{r^2(1-\frac{2M}{r})} + G_r \\ \dfrac{d}{dr}R^r{}_r = -\dfrac{(1-\frac{3M}{r})R^t{}_t+(3-\frac{5M}{r})R^r{}_r}{r(1-\frac{2M}{r})} - G_r \\ G_r = \lambda\dfrac{(\chi_{LTE}/\kappa_T)\rho M}{r^2(1-\frac{2M}{r})^{3/2}} \\ p = \dfrac{k_B}{\mu m_p}\rho T = (\Gamma-1)\epsilon \\ T = \left(-\dfrac{R^t{}_t}{4\sigma}\right)^{1/4} \\ R^{tt} = M_1^{-1}(R^{rr}, R^{tr}) \\ \chi_{\mathrm{LTE}} = \kappa_{\mathrm{ff}}(T,\rho) + \kappa_{\mathrm{bf}}(T,\rho) + \kappa_{\mathrm{KN}}(T) \end{cases}$$

References

[1] A. Stahl, M. Wielgus, M. Abramowicz, W. Kluźniak & W. Yu, A&A 546, A54 (2012).
[2] M. Wielgus, A. Stahl, M. Abramowicz & W. Kluźniak, A&A 545, A123 (2012).
[3] B. Paczyński & N. Anderson, ApJ 302, 1-10 (1986).
[4] A. Sądowski, R. Narayan, A. Tchekhovskoy & Y. Zhu, MNRAS 429, 3533 (2013).
[5] M. A. Abramowicz, G. F. R. Ellis & A. Lanza, ApJ 361, 470 (1990).
[6] V. Suleimanov, J. Poutanen & K. Werner, A&A 545, A120 (2012).

Atmospheres in Local Thermodynamic Equilibrium

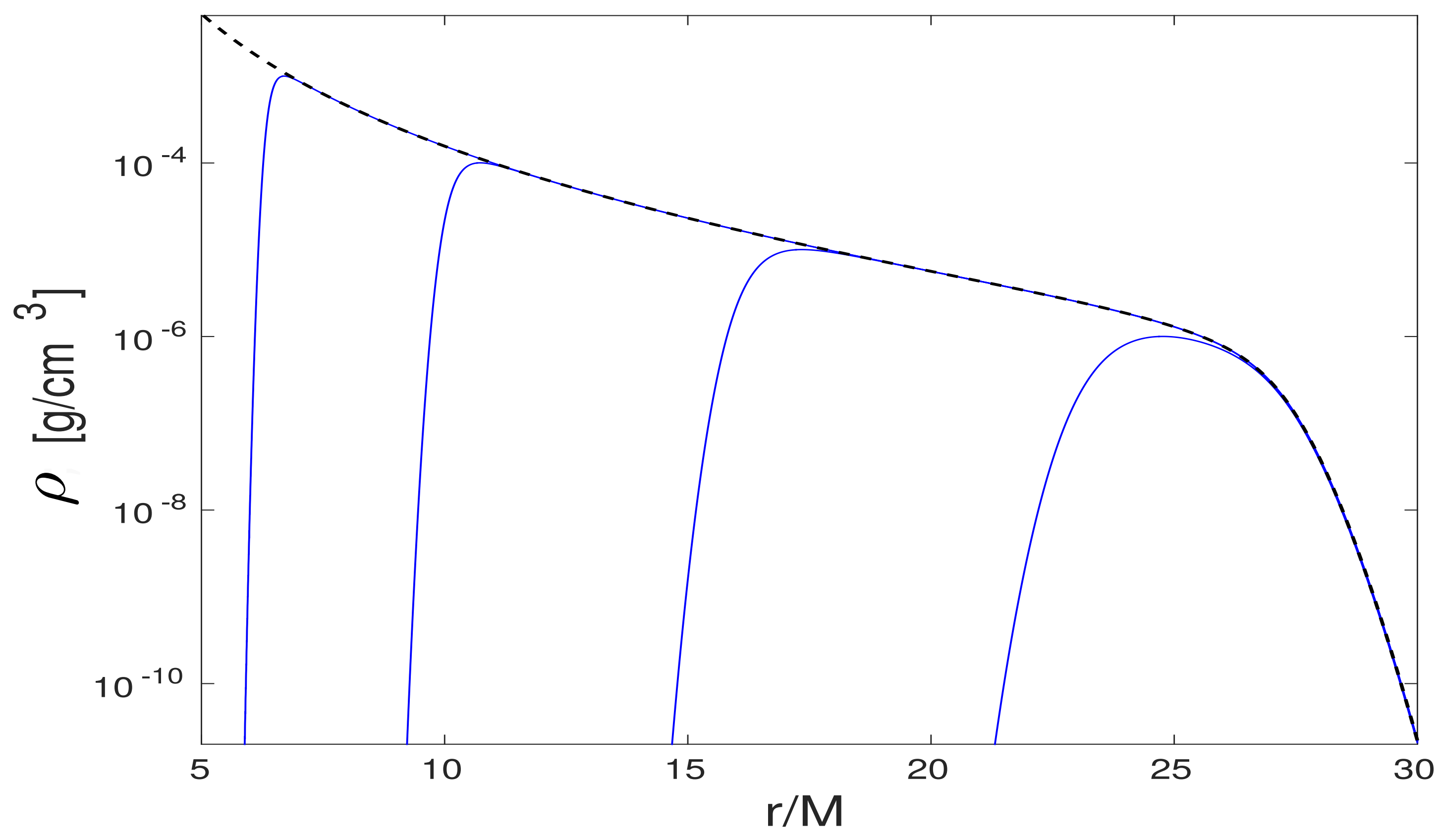
Solutions are obtained by integrating differential equations **in both radial directions**, usings the Runge-Kutta procedure, starting from radius R_E and given local density ρ_M.

At the outer boundary we then impose a condition that the radiation stress energy tensor to recover its vacuum form, known analytically [5]. Fulfilling this condition forces us to use a **numerical relaxation procedure** with which we obtain our final solutions.

$$R_E = \frac{2GM/c^2}{1-a^2(L_\infty/L_{\mathrm{Edd}})^2}$$

We find the location of pressure maximum to be similar as in the test-particle case, but with a **correction factor**, coming from the Klein-Nishina scattering model and relativistic gas thermodynamics. In the limit of cold, low-pressure gas, $a \rightarrow 1$, we recover the proper test-particle limit.

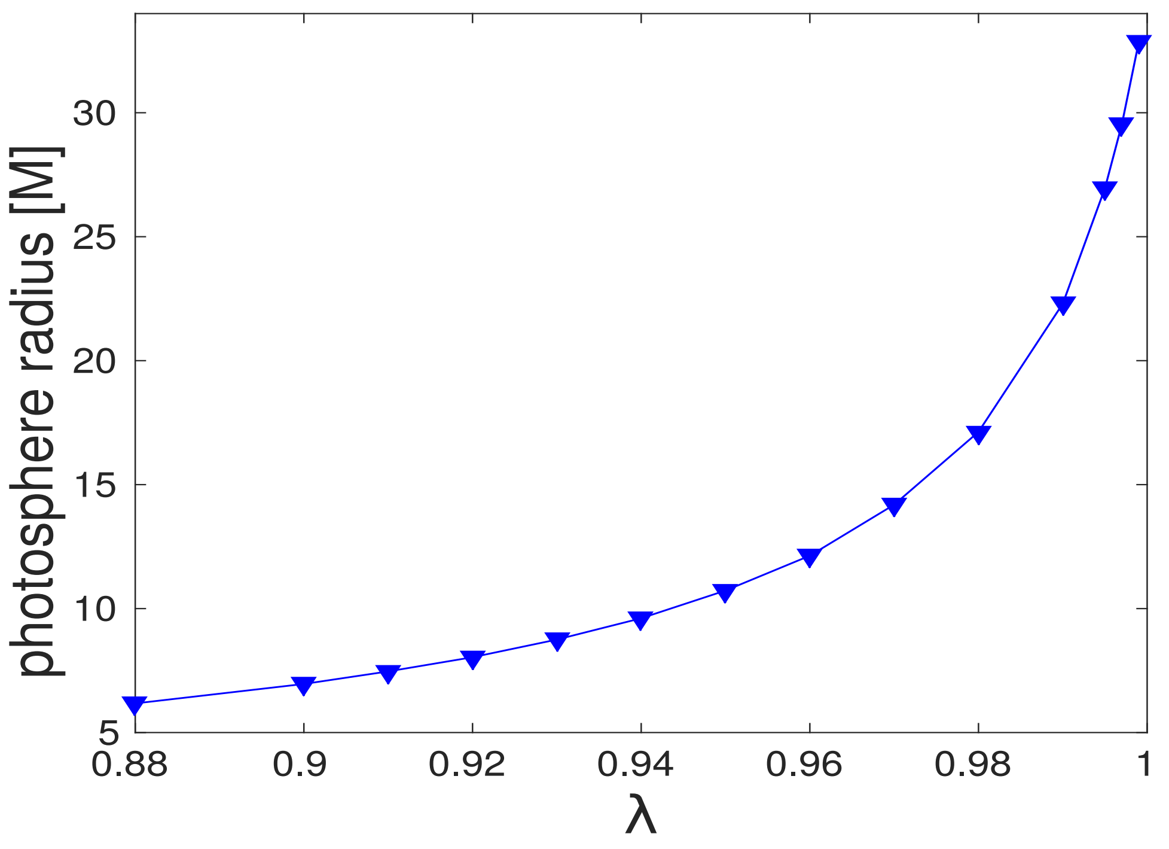
In the figure below we show the family of solutions obtained λ = 0.99.



Conclusions

For luminous stars at near Eddington luminosity, we have found a qualitatively new class of atmospheric solutions which are only present in strong gravity. The atmosphere has a **density inversion layer** and is suspended some distance above the stellar surface by radiation pressure.

Previous models [3,6] had **monotonically decaying atmospheres**.



If the atmosphere is optically thick (as in the figure above), the position of the photosphere depends on the luminosity alone (and not on the total mass of the atmosphere).

The obtained results are important for an accurate description of the physics of **photospheric expansion X-ray bursts**.

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