Self-gravitating fluid tori with charge

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From the Dolomites to the event horizon: sledging down the black hole potential well
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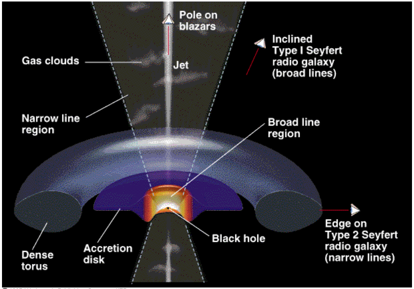
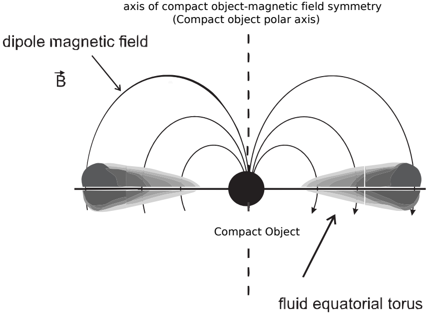
SEVENTH FRAMEWORK PROGRAMME



- Nuclei of galaxies: dusty tori and a central SMBH ($M \sim 10^6$–$10^9 M_{\odot}$).
- At distance of a few $\times 10^3$ self-gravity starts operating (Collin & Hure 2001; Karas et al. 2004).



Forces in presence

- The gravitational force of the central mass
- The self-gravitational force of the torus itself (Toomre criterion)
- The pressure of the fluid
- The magnetic force
- The centrifugal force

Rotating magnetized torus – w/ a central body, w/ charge density of the fluid

CHARGED TORI IN SPHERICAL GRAVITATIONAL AND DIPOLAR MAGNETIC FIELDS

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ABSTRACT

A Newtonian model of non-conductive, charged, perfect fluid tori orbiting in combined spherical gravitational and dipolar magnetic fields is presented and stationary, axisymmetric toroidal structures are analyzed. Matter in such tori exhibits a purely circulatory motion and the resulting convection carries charges into permanent rotation around the symmetry axis. As a main result, we demonstrate the possible existence of off-equatorial charged tori and equatorial tori with cusps that also enable outflows of matter from the torus in the Newtonian regime. These phenomena qualitatively represent a new consequence of the interplay between gravity and electromagnetism. From an astrophysical point of view, our investigation can provide insight into processes that determine the vertical structure of dusty tori surrounding accretion disks.

Euler's equation

$$\rho_{\rm m}(\partial_t v_i + v^j \nabla_j v_i) = -\nabla_i P - \rho_{\rm m}\nabla_i \Psi + \rho_e(E_i + \epsilon_{ijk} v^j B^k), \qquad (1)$$

Slaný et al (2013)

Euler's equation

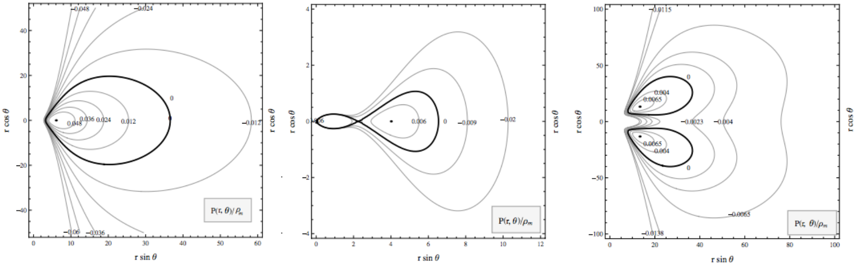
$$\nabla P = -\rho_{\mathrm{m}} \nabla \Phi - \rho_{\mathrm{m}} \nabla \Psi - \rho_{\mathrm{m}} \nabla \mathcal{M} \tag{2}$$

Integrability conditions → constraints on the spatial distribution of charge, and the corresponding angular momentum profile

- Orbital velocity: a power law of the radius
- Different distribution of the specific charge density

Equilibrium solution → maxima for the pressure function → angular momentum distribution, strength of the magnetic field.

Solving Euler's equation



- Symmetries: (i) axial, (ii) with respect to the mid-plane.
- The fluid is incompressible, $\rho_{\mathrm{m}} = \mathrm{const}$
- The integrability condition of the Euler equation $\rightarrow$ two unknown functions: the orbital velocity $v_{\phi}(R, Z)$, i.e. the way of rotation of the fluid, and the specific charge $q(R, Z)$.
- The fluid is embedded in an external magnetic field
- The torus is self-gravitating,

$$\nabla P = -\rho_{\mathrm{m}}\Phi - \rho_{\mathrm{m}}\nabla\Psi - \rho_{\mathrm{m}}\nabla\Psi_{\mathrm{Sg}} - \rho_{\mathrm{m}}\nabla\mathcal{M} \qquad (3)$$

Ψ_{Sg} is approximated by the gravitational potential of a loop in the equatorial plane (mass m centred on the axis and located in the maximum of pressure; Durand et al 1964):

$$\Psi_{\mathrm{Sg}} \sim -\frac{Gm}{r_c \pi}\sqrt{\frac{r_c}{R}}\, kK(k), \tag{4}$$

with

$$k = \frac{2\sqrt{r_c R}}{\sqrt{(r_c + R)^2 + Z^2}}. \tag{5}$$

Drawback $\rightarrow$ K diverges when its modulus $k = 1$ (i.e when the field point (R, Z) coincides with the loop radius). To avoid this singularity we add a (small) smoothing parameter λ to the modulus k,

$$\frac{2\sqrt{r_c R}}{\sqrt{(r_c + R)^2 + Z^2}} \rightarrow \frac{2\sqrt{r_c R}}{\sqrt{(r_c + R)^2 + Z^2 + \lambda^2}} \tag{6}$$

Final equation

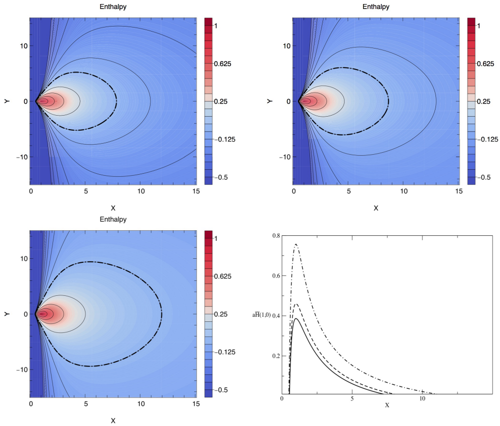
$$aH + d_t\Psi_{\mathrm{Sg}} + \Psi + b\Phi + e\mathcal{M} = \mathrm{Const}, \tag{7}$$

Contraints given by the integrability conditions

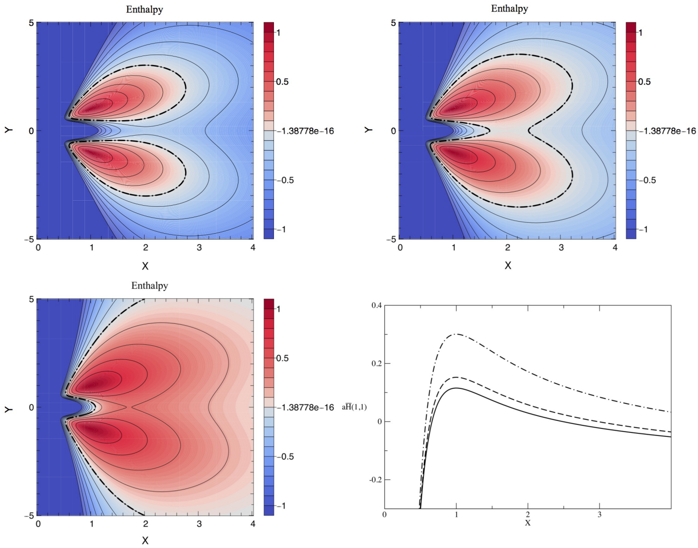
Solutions exist if H-function has a maximum $\rightarrow$ conditions on the magnetic field (value of e) and rotation (value of b). We have to choose a configuration:

- constant angular momentum vs. rigid rotation
- specific charge distribution within the torus
- strength of self-gravity (value of $d_t \equiv m/M$)

Maps of enthalpy:
choose a maximum of pressure and the b-constant $\rightarrow$ we obtain H-function



Solutions



Summary

- The condition of existence of the tori changes with the strength of self-gravity. We found equilibrium solution in rigid rotation.
- Similar morphology as in the non-selfgravitating case: we find the toroidal configuration, the closed isobars with cusps, and the toroidal off-equatorial configurations.
- The maximum of pressure rises with the value of d_t and the torus becomes thicker.
- The closed analytical form provides a way to set constraints on the existence of different configurations.

Reference: Trova A. et al. (2016), ApJSS, 226, id. 12