Neutral vector bosons in a constant magnetic field

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Motivation: Jets: What are they?

A *Jet* is an extended linear astronomical structure of matter that can be exerted by several astrophysical objects, such as:

star, stars forming regions,

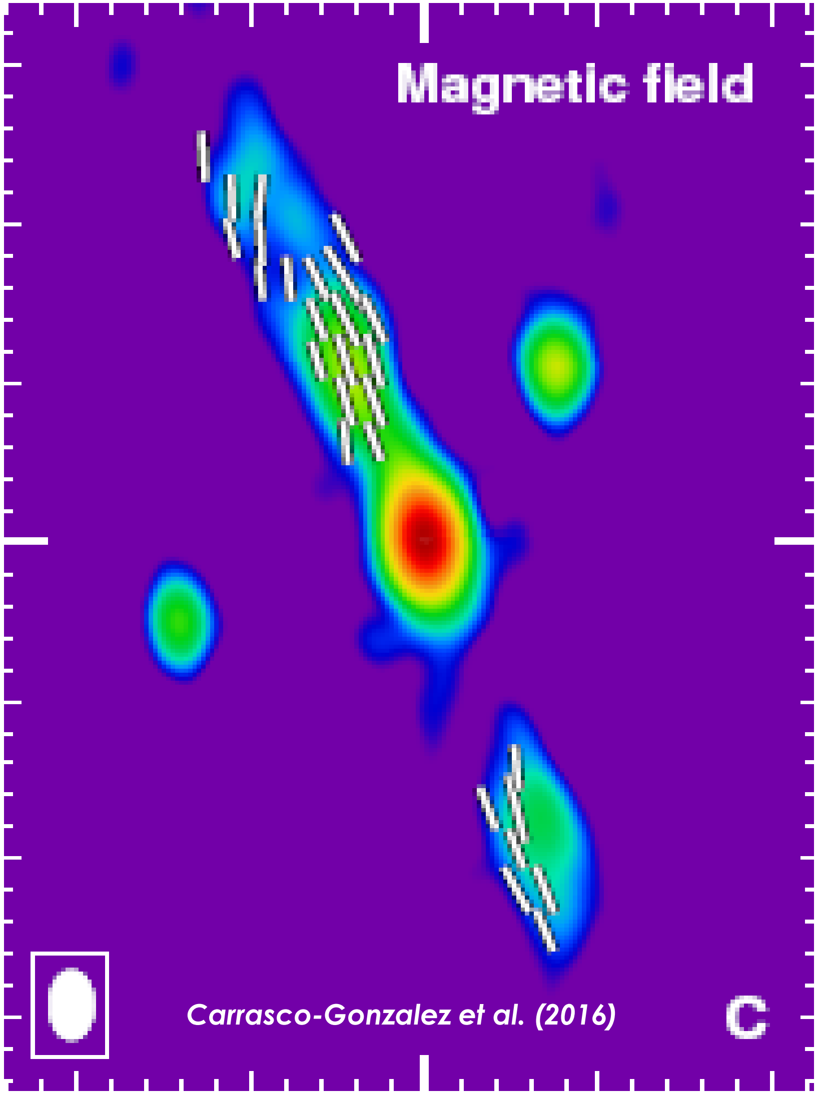
compact objects,

active galactic nuclei,

quasars,

galaxy clusters, etc.

Their one-dimensionality seems to be sustained by a self-generated magnetic field.



Our jet mechanism: Ingredients

- A **gas of electrons** inside a neutron star whose magnetic field is consider uniform and constant.

$$P_3 = -\Omega$$
$$P_\perp = -\Omega - MB.$$

With $M > 0$ the magnetization of the electron gas.

For fields large enough $P_\perp$ =0 while P_3 grows with the field.

- **Photons**

In the presence of a strong magnetic field

-the photons are forced to move along the field;

-they becomes unstable and decay in electron-positron pairs;

-it is expected that for the electron-positron pairs it is energetically more favorable to be paired than separated: positronium is formed.

H. Perez Rojas, E. Rodriguez Querts, A. Perez Martinez (2017)

Our jet mechanism: Ingredients

Electron-positron pairing leads to a **neutral vector boson field** with

Mass: $m = 2m_e$ (m_e is the electron mass)

Magnetic moment: $\kappa = 2\mu_B$ (μ_B is Bohr magneton)

Spin: $s = 1$

Electric charge: $q = 0$

Our aim is

- **to study the thermodynamical properties of a neutral spin-1 boson gas in presence of a constant magnetic field;**
- **to investigate the role of the positronium as a component of the jet.**

Neutral Spin-1 Particles

For a gas of neutral vector bosons in a constant magnetic field, we have:

- the spectrum

$$E(p_\perp, p_3, B) = \sqrt{m^2 + {p_3}^2 + {p_\perp}^2 - 2s\kappa B\sqrt{m^2 + {p_\perp}^2}}\ , \text{ with } s = -1,0,1,$$

(charged spin-1 particles $E(p_3, n, B) = \sqrt{m^2 + {p_3}^2 + (2n + 1 - 2s)|e\,B|}$)

- and the rest mass $E(0, b) = m\sqrt{1 - b}$, where $b = \frac{B}{B_c}$,

$$B_c = \frac{m}{2\kappa} \sim 4.31 \times 10^{13} G.$$

Neutral Spin-1 Particles: Thermodynamical potential

$$\Omega = \frac{1}{4\pi^2\beta}\sum_{s=1,0,-1}\int p_\perp dp_\perp\, dp_3 \ln(1-e^{-\beta(E-\mu)})(1-e^{-\beta(E+\mu)})$$

In the low temperature limit ($T \ll m \sim 1MeV$)

- the terms corresponding to $s = 0, -1$ goes to zero with T: $s = 1$;
- the antiparticle contribution is negligible;
- the thermodynamical potential can be written as:

$$\Omega = -\sqrt{\frac{E(0,b)^3}{2(2-b)^2\pi^5\beta^5}}L_{5/2}(e^{\beta\mu'})$$

where $\boldsymbol{\mu' = \mu - E(0,b)}$ and $L_n(x) = \sum_{i=1}\frac{x^i}{i^n}$.

Neutral Spin-1 Particles: Particle density and condensation

- The particle density is $N = \sqrt{\frac{E(0,b)^3}{2(2-b)^2\pi^5\beta^3}} L_{3/2}\left(e^{\beta\mu'}\right)$.

The equation for N does not diverge when $\mu' = 0$ $\Rightarrow$ the gas shows usual BEC!!

- Critical temperature $T_c = \frac{1}{E(0,b)} \sqrt[3]{\frac{2(2-b)^2\pi^5 N^2}{\zeta(3/2)}} \xrightarrow[b\to 1]{} \infty$

where $\zeta(x)$ is the Riemann zeta fucntion.

- The number of particles out of the condensate

$$N_{oc} = \sqrt{\frac{E(0,b)^3}{2(2-b)^2}} T^3 \zeta\,(3/2) \xrightarrow[\substack{T\to 0\\ b\to 1}]{} 0$$

Phase diagram: $T_c = \frac{1}{E(0,b)} \sqrt[3]{\frac{2(2-b)^2 \pi^5 N^2}{\zeta(3/2)}}$

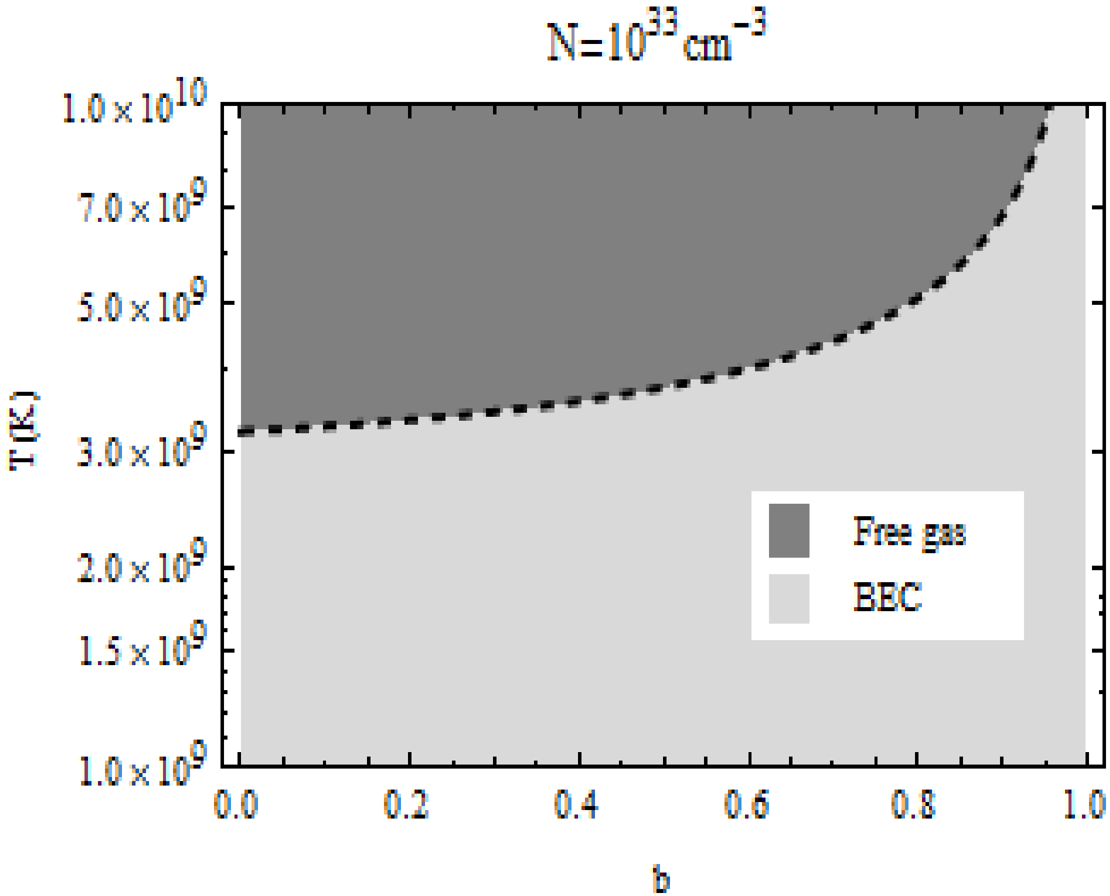


Figure 1. Phase diagram T vs. b.

Neutral Spin-1 Particles: Magnetization and Self-magnetization

$$M = -\frac{\partial\Omega}{\partial B} = \frac{\kappa m}{E(0,B)} N$$

$$B - 4\pi M = H$$
$$H = 0$$

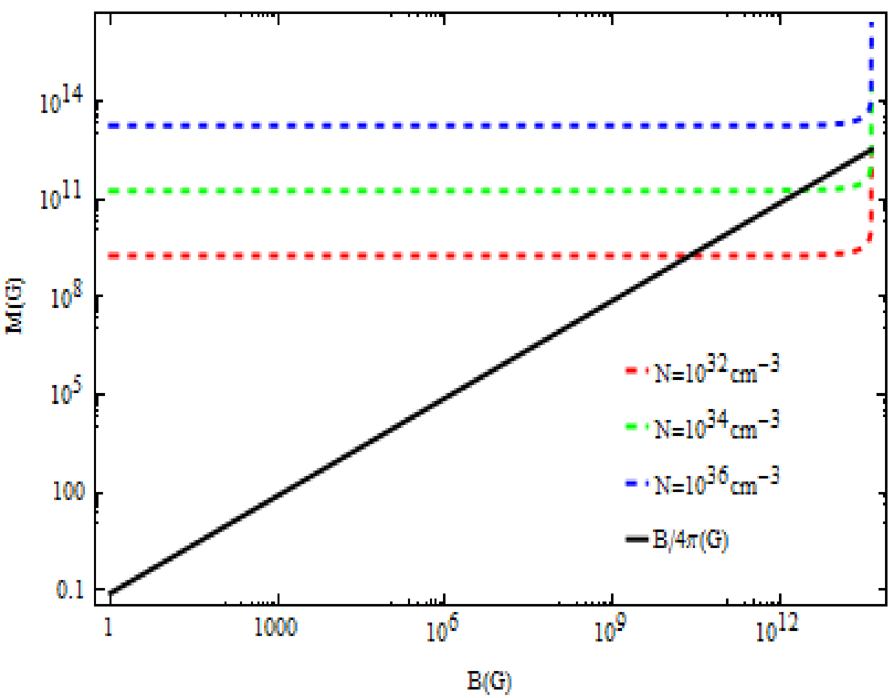


Figure 2. Magnetization as a function of the magnetic field. We have also plotted $^{B}/_{4\pi}$.

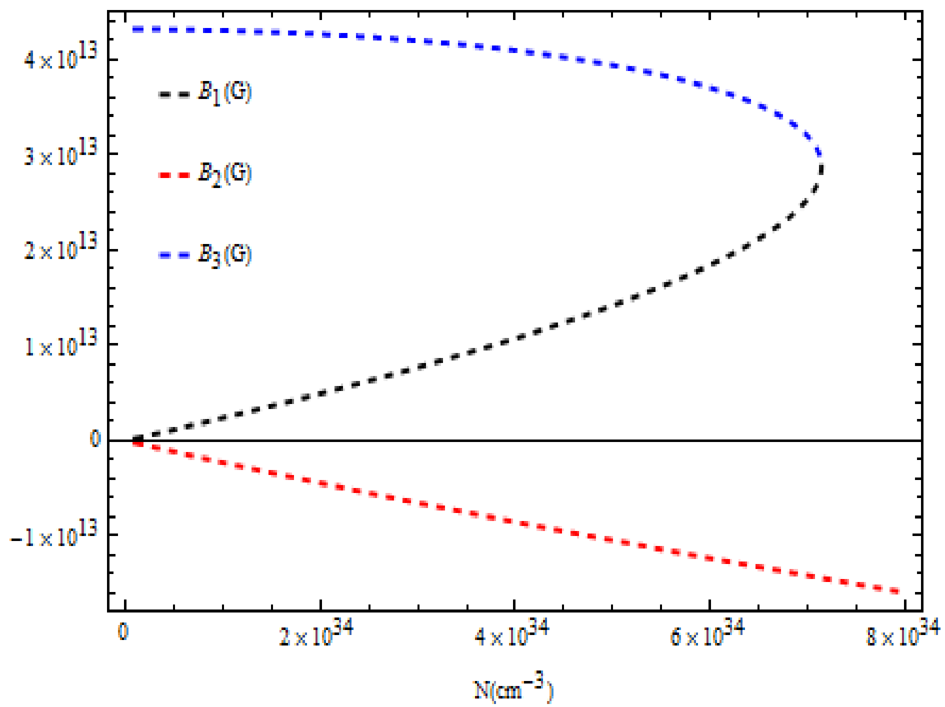


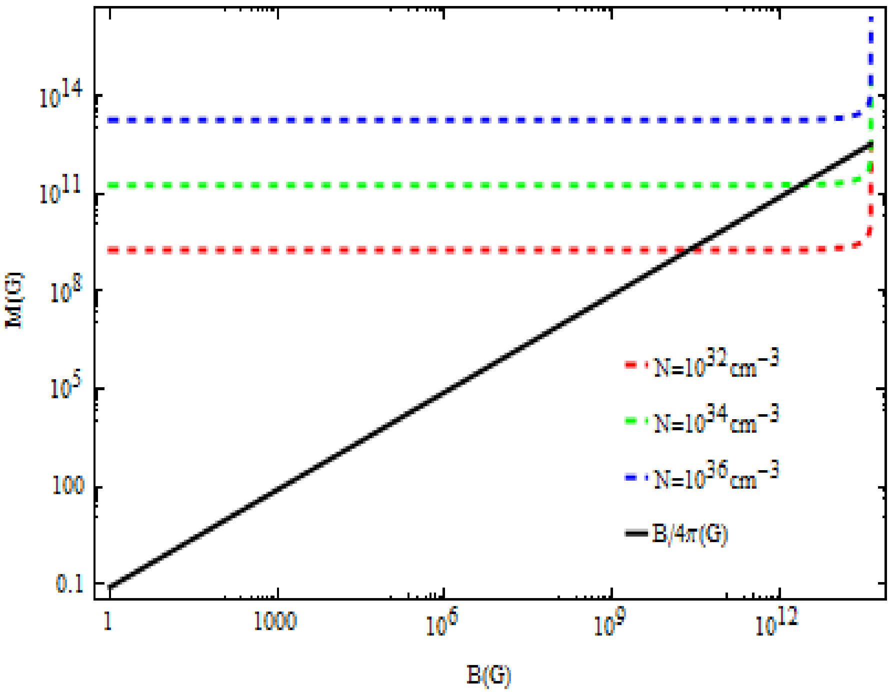
Figure 3. The solutions of the self magnetization equation as a function of particle density N. Only the black dashed curve is physically meaningful.

Neutral Spin-1 Particles: Magnetization and Self-magnetization

$$M = -\frac{\partial \Omega}{\partial B} = \frac{\kappa m}{E(0,B)} N$$

$$N_c = 7.3 \times 10^{34} cm^{-3}$$

$$B = {}^{2}/_{3}\, B_c \sim 10^{13} G$$



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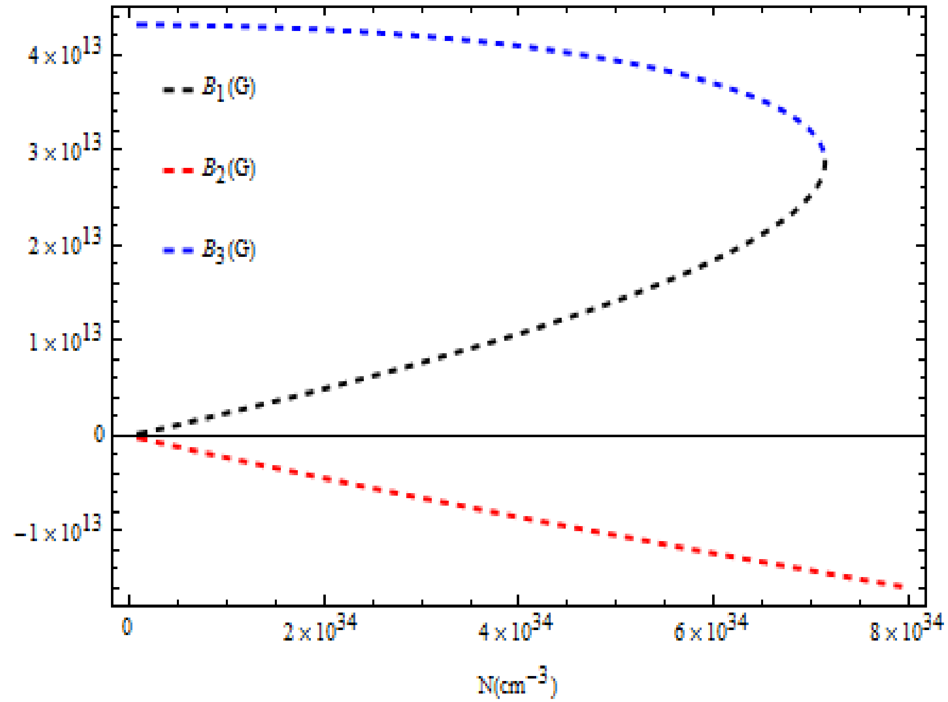

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Neutral Spin-1 Particles: Results

1. The effective rest mass is a decreasing function of the magnetic field and becomes zero when $B \to B_c$.

2. The gas undergoes a phase transition to a usual BEC when the field increases or the temperature decreases.

3. The magnetization of the gas is a positive quantity that increases with the field and diverges when $B = B_c \sim 10^{13} G$.

4. For particle densities under a critical value $N_c \sim 10^{34} cm^{-3}$ the gas can maintain a self-generated magnetic field.

Neutral Spin-1 Particles: Implications

1. Positronium formation is energetically favourable.

2. Positronium contribution to the pressures in the jet should be negligible.

3. Postironium is a good candidate to be the origin of the self-sustained magnetic field of the jet.

Final picture: ***a quantum self-magnetized jet***

- A dense electron gas which may expand and push matter and radiation linearly.
- A gas of neutral vector bosons (positronium) that can self-maintain the magnetic field.

Neutral Spin-1 Particles: Implications

This work could be useful in modeling the mechanisms that sustain the strong magnetic fields showed by astrophysical phenomena!

But also to give a thermodynamical description of any other neutral vector boson gas!

Thanks!