The mechanism by which gamma-ray pulsars shine might be reproducible in a laboratory. This claim is supported by three observations: (i) properly focusing a few PW optical laser gives an electromagnetic field in the so-called Aristotelian regime, when a test electron is radiation-overdamped; (ii) the Goldreich-Julian number density of this electromagnetic field (the number density of elementary charges needed for a nearly full conversion of optical power into gamma-rays) is of order the electron number density in a solid; (iii) above about 50PW, the external source of electrons is not needed – charges will be created by a pair production avalanche.

I. INTRODUCTION

It appears that a gamma-ray pulsar can be created in a laboratory. Real pulsars are efficiently converting the large-scale Poynting flux into gamma-rays (up to order-unity efficiency for a weak axisymmetric pulsar, [1] and references therein). The laboratory pulsar is expected to efficiently convert optical light into gamma-rays.

At the level of estimates, the conditions needed for an efficient Poynting-to-gamma conversion appear to be reproducible in a laboratory. All one needs is (i) Aristotelian number above one, meaning radiation damping stronger than inertia, and (ii) the right (namely Goldreich-Julian, [2]) number density of electrons. We discuss these two conditions in turn.

II. ARISTOTELIAN REGIME

Consider a test electron in the electromagnetic field of generic geometry, \(|E^2 - B^2| \sim |E \cdot B| \sim F^2 > 0\), with characteristic length scale \(\lambda\), and characteristic time scale \(\lambda/c\). Let us estimate the characteristic Lorentz factor of the electron, \(\gamma\). On the one hand, there exists a maximal possible \(\gamma\) associated to the full “potential drop” of the field:

\[
\gamma_{\text{max}} \sim \frac{e F \lambda}{m c^2},
\]

(1)

where \(F \sim E \sim B\) is the characteristic value of electric and magnetic fields, \(e\) is the electron charge, \(m\) is the electron mass. On the other hand, there exists a terminal Lorentz factor at which the radiation damping balances the Lorentz force:

\[
\gamma_{\text{term}} \sim \left(\frac{F \lambda^2}{e}\right)^{1/4}.
\]

(2)

The electron is radiation-overdamped (the field is in the Aristotelian regime) if the terminal Lorentz factor is reached in less than the characteristic length scale, that is if

\[
\gamma_{\text{max}} \gtrsim \gamma_{\text{term}}.
\]

(3)

Estimating the field from

\[
L \sim c \lambda^2 F^2,
\]

(4)

where \(L, \text{erg/s},\) is the laser power, we write the condition of radiation overdamping as

\[
\text{Ar} \equiv \frac{L}{L_e} \left(\frac{\lambda}{r_e}\right)^{-2/3} \gtrsim 1,
\]

(5)

where we have defined the dimensionless Aristotle number \(\text{Ar}\), with \(L_e \equiv \frac{mc^2}{r_e} = 8.7 \times 10^{16} \text{erg/s} – \) the classical electron luminosity, and \(r_e = \frac{e^2}{4\pi mc} = 2.8 \times 10^{-13} \text{cm} – \) the classical electron radius.

Assuming that a (split) laser pulse of power \(L_{PW} \times 10^{22} \text{erg/s}\) is focused onto a region of size \(\lambda\mu \times 10^{-4} \text{cm}\), we get an Aristotle number

\[
\text{Ar} \sim 0.2 L_{PW} \lambda^{-2/3} \mu,
\]

(6)

For \(\lambda\mu = 0.5\) and \(L_{PW} > 3\), we have \(\text{Ar} > 1\).

In Aristotelian regime, \(\text{Ar} \gtrsim 1\), the work done by the field goes into emission of curvature photons rather than into accelerating electrons. The characteristic photon energy is

\[
\epsilon \sim \frac{mc^2}{\alpha} \text{Ar}^{3/8},
\]

(7)

where \(\alpha\) is the fine structure constant. Pulsars have \(\text{Ar} \gg 1\) and emit above about 1 GeV. “Aristotelian lasers” should emit above about 100MeV.

III. GOLDREICH-JULIAN NUMBER DENSITY

Each electron emits gamma-rays at a power \(\sim e F c\); if we want to convert the entire laser pulse into gamma-rays, the number density of electrons \(n\) should be

\[
n \sim \frac{L}{\lambda^3 e F c} \sim \frac{c \lambda^2 F^2}{\lambda^3 e F c} \sim \frac{F}{e \lambda^2}.
\]

(8)

In pulsar physics, the last expression is known as the Goldreich-Julian density – this is the number density of elementary charges needed to noticeably alter the external field \(\sim F\). Numerically,

\[
n_{\text{GJ}} \sim 1.2 \times 10^{23} L_{PW}^{1/2} \lambda^{-2} \text{cm}^{-3}
\]

(9)

is of order the number density in a solid.
We also note that above about 50PW, the pair avalanche will (over) produce the necessary charge density starting from a single seed charge as described in [3]: a seed charge emits gamma rays; gamma-rays pair produce in external magnetic field; pairs then emit gamma-rays, etc.

IV. CONCLUSION

When powerful lasers are properly focused on a target or even on vacuum, an efficient optical to gamma-ray conversion should occur, enabled by the same mechanism by which the gamma-ray pulsars shine.