Laboratory gamma-ray pulsar

Andrei Gruzinov
CCPP, Physics Department, New York University, 4 Washington Place, New York, NY 10003

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. 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 \(\gamma\). 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:

\[
\gamma_{\text{max}} \sim \frac{eF\lambda}{mc^2},
\]

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:

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

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

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

Estimating the field from

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

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

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

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

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

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

For \(\lambda_\mu = 0.5\) and \(L_{\text{PW}} > 3\), 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

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

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

III. GOLDREICH-JULIAN NUMBER DENSITY

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

\[
\begin{aligned}
n & \sim \frac{L}{\lambda e\epsilon Fe} \sim \frac{e\lambda^2F^2}{\lambda e\epsilon Fe} \sim \frac{F}{e\lambda}.
\end{aligned}
\]

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,

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

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.

[1] A. Gruzinov, arXiv:1402.1520 (2014)
[2] P. Goldreich, W. H. Julian, Astrophys. J. 157, 869 (1969)
[3] M. A. Ruderman, P. G. Sutherland, Astrophys. J. 196, 51 (1975)