Fireball in Fast Radio Bursts

Kunihito Ioka[1]

[1] *Center for Gravitational Physics and Quantum Information, Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*

ABSTRACT

A fireball of radiation plasma created near the surface of a neutron star (NS) expands under its own pressure along magnetic field lines, and produces photon emission and relativistic matter outflow. We comprehensively classify the expanding fireball evolution into five cases and obtain the photospheric luminosity and the kinetic energy of the outflow, taking into account key processes; lateral diffusion of photons escaping from a magnetic flux tube, effects of strong magnetic field, baryon loading from the NS surface, and radiative acceleration via cyclotron resonant scattering, some of which have not been considered in the context of gamma-ray bursts. Applying our model to magnetar bursts with fast radio bursts (FRBs), in particular the X-ray short bursts from SGR 1935+2154 associated with the Galactic FRB 20200428A, we show that the burst radiation can accelerate the outflow to high Lorentz factor with sufficient energy to power FRBs.

We also investigate parametric decay of a circularly polarized Alfven wave propagating along a constant magnetic field in a relativistic magnetohydrodynamical (MHD) plasma. Perturbative analyses are performed in the fluid comoving frame, forcusing on the case that the Alfvén velocity is larger than the sound velocity, even up to relativistic one, i.e., high σ (ratio of the magnetic to matter energy density). We find that the dispersion relation possess an unstable mode that parent Alfvén waves decay into forward-propagating acoustic waves (longitudinal slow MHD waves) and backward-propagating Alfvén waves, for any σ but with suppressed by $\sigma^{-1/2}$ at high σ. The acoustic waves shortly become nonlinear, leading to shock dissipation. We discuss implications for FRBs including that Alfvén waves preferentially heat high density plasma, boosting a fireball that transfers the kinetic energy along a magnetic field line to the FRB emission site.

1. SELF-INTRODUCTION

Research: Theoretical astrophysics (Gamma-ray bursts, Fast radio bursts, Electromagnetic counterparts to gravitational waves, High energy neutrinos, Gamma-rays, Cosmic rays, etc.)

Education: Ph.D. in Physics, Kyoto University, Japan (Mar. 2001)
M.S. in Physics, Kyoto University, Japan (Mar. 1998)
B.S. in Physics, Kyoto University, Japan (Mar. 1996)

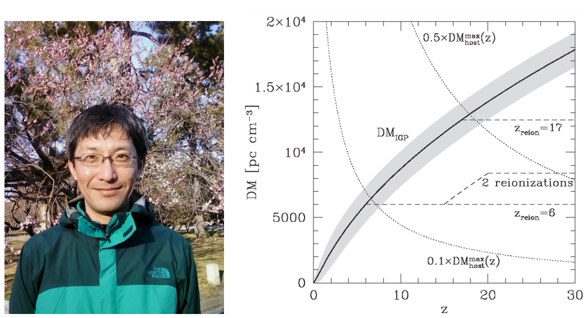

Figure 1. I may be known for the DM-z plot in Ioka (2003).

kunihito.ioka@yukawa.kyoto-u.ac.jp

Positions: JSPS fellow, Department of Earth and Space Science, Osaka University, Japan (Host: Prof. Fumio Takahara; Apr. 2001)
Postdoctoral fellow, Physics Department and Center for GravitationalWave Physics, Pennsylvania State University (Host: Prof. Peter Mészáros; Apr. 2004)
Assistant Professor, Department of Physics, Kyoto University (Apr. 2005)
Associate Professor, Institute of Particle and Nuclear Studies, KEK (Oct. 2007)
Professor, Yukawa Institute for Theoretical Physics, Kyoto University (Feb. 2016)

Papers: "The Cosmic Dispersion Measure from Gamma-Ray Burst Afterglows: Probing the Reionization History and the Burst Environment", Ioka (2003)
"Cosmological Fast Radio Bursts from Binary White Dwarf Mergers", Kashiyama et al. (2013)
"A Binary Comb Model for Periodic Fast Radio Bursts", Ioka & Zhang (2020),
"Fast Radio Burst Breakouts from Magnetar Burst Fireballs", Ioka (2020)
"Binary Comb Models for FRB 121102", Wada et al. (2021)

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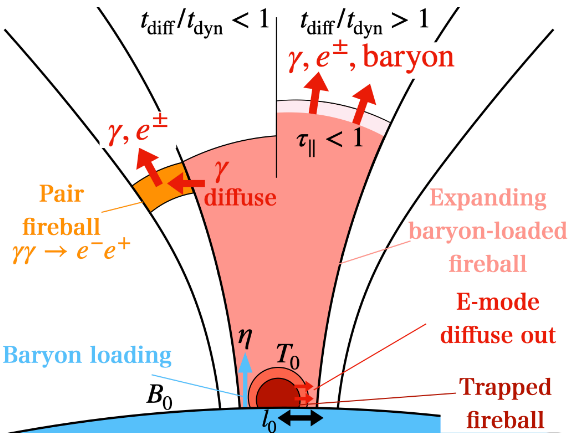

Figure 2. A fireball expanding along magnetic field lines releases radiation for X-ray bursts and generates the kinetic energy for FRBs.

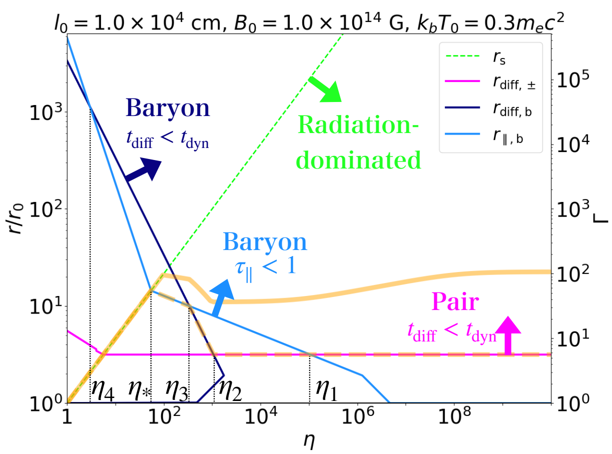

Figure 3. The characteristic radii (normalized by the stellar radius) and Lorentz factor of an outflow with dimensionless entropy η. The maximum Lorentz factor (*orange thick line*) is $\Gamma \sim 10^2$.

2. EXPANDING FIREBALL

How is the energy transferred to the emission region of FRBs? In a magnetar model, the energy is most likely generated on the surface of a neutron star. On the other hand, the emission region is thought to be far up in the magnetosphere or even outside it. There are basically two ways of energy transfer: kinetic flux and Poynting flux.

In the Galactic FRB, the X-ray bursts were $\sim 10^3$ times brighter than the FRBs. The X-ray bursts are the main and the FRBs are the sub. We should first explain the X-ray bursts, and in that framework, the FRBs should be modeled.

We show that a fireball that explains the X-ray bursts can also produce enough kinetic energy for the FRBs (Wada & Ioka 2022). An easy way is to mix baryon. Even without baryon, the radiative acceleration beyond the photospheric radius via resonant cyclotron scatterings could achieve this.

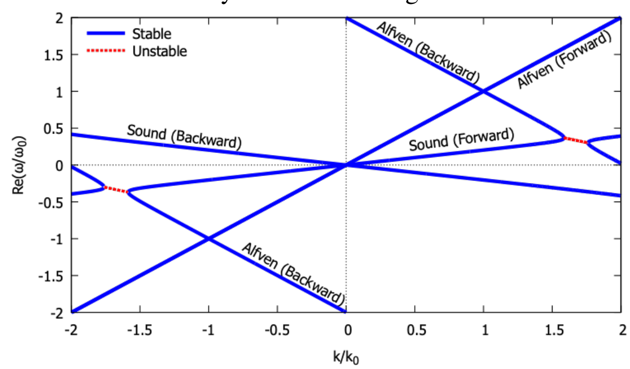

Figure 4. The dispersion relation that shows the instability. The frequency has an imaginary part at the red dotted line.

3. DECAY OF ALFVÉN WAVES

The energy is also transferred by Poynting flux, in particular Alfvén waves. In the solar physics, Alfvén waves play an important role in the coronal heating and wind acceleration. We extend the analogy to relativistic MHD plasma.

Ishizaki & Ioka (2022) find the decay rate at high σ and low temperature is about

$$\frac{\omega_i}{\omega_0} \sim \frac{1}{2}\frac{\delta B}{B}\left(\frac{v_A}{c_s}\right)^{1/2}\sigma^{-1/2}, \quad (1)$$

which implies that the Alfvén waves could decay in a fireball. We could not find a paper that derived this simple formula, but we may miss it. Please let us know the relevant papers.

I would like to thank S. Kulkarni for letting me know my misunderstanding about the format of this summary.

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