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INDUCED SCATTERING LIMITS ON FAST RADIO BURSTS FROM STELLAR CORONAE

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ABSTRACT

The origin of fast radio bursts remains a puzzle. Suggestions have been made that they are produced within the Earth's atmosphere, in stellar coronae, in other galaxies, or at cosmological distances. If they are extraterrestrial, the implied brightness temperature is very high, and therefore the induced scattering places constraints on possible models. In this paper, constraints are obtained on flares from coronae of nearby stars. It is shown that the radio pulses with the observed power could not be generated if the plasma density within and in the nearest vicinity of the source is as high as is necessary to provide the observed dispersion measure. However, one cannot exclude the possibility that the pulses are generated within a bubble with a very low density and pass through the dense plasma only in the outer corona.

Key words: radiation mechanisms: non-thermal – scattering – stars: coronae

1. INTRODUCTION

Since the first fast radio burst (FRB) was discovered (Lorimer et al. 2007), nearly a dozen such events have been reported (Keane et al. 2011; Thornton et al. 2013; Burke-Spolaor & Bannister 2014; Spitler et al. 2014; Petroff et al. 2015; Ravi et al. 2015). Inasmuch as these millisecond flares exhibit very large dispersion measures significantly exceeding the Galactic one (see, however, Bannister & Madsen 2014), the currently favored interpretation is that they occur at cosmological distances. The implied tremendous energy release (isotropic equivalent $\sim 10^{40}$ erg) in the radio band should be attributed to exotic events; among those discussed are magnetar hyper flares (Popov & Postnov 2007, 2013; Thornton et al. 2013; Katz 2014; Lyubarsky 2014), a supernova explosion in a binary containing a neutron star (Egorov & Postnov 2009), the collapse of a supermassive neutron star (Falcke & Rezzolla 2014; Zhang 2014), binary white dwarf, or neutron star merger (Keane et al. 2012; Kashiyama et al. 2013; Totani 2013; Lipunov & Pruzhinskaya 2014; Ravi & Lasky 2014), the evaporation of a primordial black hole (Keane et al. 2012), an asteroid/comet impact with a neutron star (Geng & Huang 2015), supergiant pulses from pulsars (Connor et al. 2015; Katz 2015), and quark nova (Shand et al. 2015). The possible terrestrial origin is discussed by Burke-Spolaor et al. (2011) and Kulkarni et al. (2014).

Loeb et al. (2014) suggested that the sources of FRBs are flaring stars in our Galaxy. In this case, the large dispersion measure is due to the stellar corona with the density $10^{8\text{–}9}$ cm^{-3} extended to the distance $\sim 10^{12\text{–}13}$ cm. Maoz et al. (2015) added credibility to the model, finding flare stars in FRB fields and also showing that the previous concerns about too high free–free absorption in the corona (Luan & Goldreich 2014) or possible significant deviations from the f^{-2} dependence of the pulse arrival times (Dennison 2014; Tuntsov 2014) may be alleviated. Even though the required energy release is not extraordinarily high in this model, the inferred brightness temperature is still very high, thus some coherent radiation mechanism is assumed. The authors mention the cyclotron instability as a candidate. However, independently of the radiation mechanism, the induced scattering on the relatively dense plasma in the corona should unavoidably affect the outgoing radiation. It will be demonstrated in this paper that FRBs could be generated in coronae of nearby stars only if the density within and in the nearest vicinity of the source does not exceed $\sim 10^5$ cm^{-3}, much smaller than necessary to explain the observed high dispersion measure. The only option available for having an FRB from a star in our Galaxy is to assume that the flare occurs in a low-density bubble embedded in a high-density corona.

2. INDUCED COMPTON SCATTERING IN THE VICINITY OF THE SOURCE

The kinetic equation for the induced Compton scattering in the non-relativistic plasma is written as (e.g., Wilson 1982)

$$\frac{dn(\nu,\,\boldsymbol{\Omega})}{dt} = \frac{3\sigma_{\mathrm{T}}}{8\pi} N \frac{h}{m_e c} n(\nu,\,\boldsymbol{\Omega}) \times \int (\boldsymbol{e}\cdot\boldsymbol{e}_1)^2 (1-\boldsymbol{\Omega}\cdot\boldsymbol{\Omega}_1) \times \frac{\partial \nu^2 n(\nu,\,\boldsymbol{\Omega}_1)}{\partial\nu} d\boldsymbol{\Omega}_1; \quad (1)$$

where $n(\nu,\,\boldsymbol{\Omega})$ is the photon occupation number in the direction $\boldsymbol{\Omega}$, N is the electron number density, $\boldsymbol{e}$ is the polarization vector, and

$$\frac{d}{dt} = \frac{\partial}{\partial t} + c(\boldsymbol{\Omega}\cdot\boldsymbol{\nabla}) \quad (2)$$

is the derivative along the ray.

The induced scattering does not affect the escape time of photons from the source, but redistributes photons toward lower frequencies where they are ultimately absorbed (Syunyaev 1971). The kinetic equation for the induced scattering may be presented in the form

$$\frac{dn}{dt} = A\{n\}n. \quad (3)$$

The process is efficient if the frequency redistribution rate, $A\{n\}$, exceeds the escape rate (for optically thin sources, the last is just the light travel time, r_0/c).

Within and in the nearest vicinity of the source, the radiation subtends a large angle; therefore, for rough estimates, one can neglect the angular dependence of n in the rhs of Equation (1), which yields

$$\frac{dn}{dt} = \sigma_T N \frac{\hbar n}{m_e c} \frac{\partial \nu^2 n}{\partial \nu}. \tag{4}$$

In the spatially homogeneous case, this equation is directly obtained from the Kompaneets equation by passing to the limit as the radiation brightness temperature significantly exceeds the electron temperature (e.g., Syunyaev 1971). It follows immediately from Equation (4) that the radiation with the brightness temperature $T_b \equiv \hbar\nu n/k_B$ is unable to escape from a source with the Thomson depth τ_T if (Syunyaev 1971; Wilson 1982; Coppi et al. 1993)

$$\tau_{\rm ind} \equiv \frac{k_B T_b}{m_e c^2} \tau_T > 1. \tag{5}$$

The effective optical depth, $\tau_{\rm ind}$, is the ratio of the escape time to the frequency redistribution time, therefore, at $\tau_{\rm ind} \gg 1$, only a fraction $1/\tau_{\rm ind}$ of photons escapes; the rest is redistributed toward smaller frequencies. The total number of photons is conserved in the scattering process; therefore, the photon phase density and the brightness temperature increase when the radiation is redistributed toward smaller frequencies so that the rate of redistribution increases further out. If no competitive process came into play, the photon Bose condensation would occur at zero frequency (Zel'Dovich & Levich 1969; Zel'Dovich et al. 1972). In reality, the photons are eventually absorbed because when the frequency approaches the plasma frequency, the free–free absorption coefficient goes to infinity.

Typical parameters of the FRB are the pulse duration, $\Delta t \sim 1$ ms, the wavelength, $\lambda \approx 20$ cm, and the flux, $S \sim 1$ Jy. The size of the source is limited by the sound travel time, namely,

$$r_0 \leqslant \Delta t v_s = 3 \times 10^7 \frac{v_s}{c} \Delta t_{-3}\ {\rm cm}, \tag{6}$$

where $\Delta t_{-3} = \Delta t/1$ ms, and, v_s is the sound velocity in the source. In some cases, the sound velocity should be substituted by the Alfvén velocity, although in any event, these velocities are below the speed of light. One can now estimate the brightness temperature in the burst as

$$T_b = \frac{\lambda^2 S D^2}{2\pi r_0^2 k_B} > 5 \times 10^{21} \lambda_{20}^2 S_{\rm Jy} \left(\frac{D_{300} c}{\Delta t_{-3} v_s}\right)^2 {\rm K}, \tag{7}$$

where $\lambda_{20} = \lambda/20$ cm, $S_{\rm Jy} = S/1$ Jy, and $D_{300} = D/300$ pc. If the density in the corona is $N = 10^9 N_9\ {\rm cm}^{-3}$, the effective optical depth of the FRB source for the induced Compton scattering is estimated as

$$\tau_{\rm ind} = \frac{k_B T_b}{m_e c^2} \sigma_T N r_0 > 1.6 \times 10^4 \frac{\lambda_{20}^2 S_{\rm Jy} D_{300}^2 N_9}{\Delta t_{-3}} \frac{c}{v_s}. \tag{8}$$

It can be noted that the radiation with the brightness temperature observed in FRBs could not escape from the source if the plasma density is as high as is necessary to provide the observed dispersion measure.

3. INDUCED COMPTON SCATTERING IN OUTER CORONA

In the previous section, we considered the induced scattering within and in the nearest vicinity of the source, and thus condition (5) was used, which assumes that the radiation subtends a large solid angle. The conclusion was reached that the radiation with the required brightness temperature could not escape if the plasma density is the same as in the corona. However, one can speculate that the FRB is produced within a bubble with a density much smaller than that in the main body of the corona. Alternatively, one can assume that the magnetic field in the vicinity of the source is so high that the Larmor frequency significantly exceeds the radiation frequency; then the scattering is suppressed for the extraordinary mode (in which the rotation of the polarization vector is opposite to the electron Larmor rotation). In both of these cases, one can find parameters such that the effective optical depth for the induced scattering within and around the source remains less than unity. However, one must still assume that the emitted radiation passes through a dense and weakly magnetized outer corona in order to obtain the observed f^{-2} dependence of the pulse arrival time. In this section, we consider the induced scattering in the corona far from the source.

At any point far from the source, the radiation field subtends a small solid angle forming a narrow local radiation beam. The induced scattering rate is proportional to the number of photons already available in the final state, hence, the scattering initially occurs within the primary beam where the radiation density is high. However, when the primary radiation is highly directed, the recoil factor $1 - \boldsymbol{\Omega} \cdot \boldsymbol{\Omega}_1$ in the rhs of Equation (1) makes the scattering within the beam inefficient. In this case, the scattering outside the primary radiation beam dominates (Coppi et al. 1993) because, according to Equation (3), even weak background radiation (created, e.g., by spontaneous scattering) grows exponentially in the course of the induced scattering so that the energy of the scattered radiation becomes eventually comparable with the energy density in the primary beam.

The effect of the induced scattering on short, bright radio pulses passing a plasma screen at large distances from the source was studied by Lyubarsky (2008). He introduced the effective optical depth as

$$\tau_{\rm ind,pulse} = \frac{3\sigma_T}{8\pi} \frac{\lambda^2 N S}{m_e c} \left(\frac{D}{r}\right)^2 Z, \tag{9}$$

where the factor Z is determined by the pulse duration and shape, r the distance from the source to the scattering screen. In the simplest case of a rectangular pulse, $Z = \Delta t$. This expression assumes that the width of the screen exceeds the pulse width, $c\Delta t$; then the effective optical depth is independent of the screen width. It is shown that the induced scattering does not affect the pulse if

$$\tau_{\rm ind,pulse} \lesssim 10. \tag{10}$$

The factor of 10 arises due to the fact that, in this situation, the radiation at large angles to the propagation direction of the primary radiation should have enough time to grow from a very low background level.

Substituting typical parameters of FRB, one can write the transparency condition (10) as

$$r > 10^9 \lambda_{20} D_{300} N_9^{1/2} S_{\rm Jy}^{1/2} \Delta t_{-3}^{1/2}\ {\rm cm}. \tag{11}$$

One sees that the induced scattering in the outer corona could not affect the propagation of the pulse.

4. RAMAN SCATTERING IN OUTER CORONA

The propagation of a high brightness temperature pulse may also be affected by induced Raman scattering. In this process, the photon decays into another photon and a Langmuir plasmon. In other words, the radio emission is scattered off Langmuir plasmons, which it generates. The scattering rate depends on the intensity of Langmuir turbulence, which is limited by the Landau damping and collisional decay of plasmons. One can neglect the plasmon decay if the radiation power is high enough; in terms of the observed parameters the critical observed flux, above which one can neglect the plasmon decay, is found as (Thompson et al. 1994; Lyubarsky 2008)

$$S_\kappa = \frac{16\pi m_e \nu\nu_p}{3\sigma_{\rm T} cN}\left(\frac{r}{D}\right)^2\kappa, \qquad (12)$$

where ν_p is the plasma frequency and κ is the plasmon decay rate. If the last is determined by the electron–ion collisions, one finds

$$S_\kappa = 1.3\times 10^{-3}\frac{N_9^{1/2}}{\lambda_{20}T_6^{3/2}}\left(\frac{r_9}{D_{300}}\right)^2 {\rm Jy}, \qquad (13)$$

where $T = 10^6 T_6$ K is the plasma temperature.

In order to get the maximal scattering rate, let us neglect plasmon decay. In this case, the effective optical depth with respect to the induced Raman scattering for a pulse with the duration Δt is found as (Lyubarsky 2008)

$$\tau_{\rm R} = \frac{3\sigma_{\rm T} cNS}{m_e \nu\nu_p}\left(\frac{D}{r}\right)^2\Delta t. \qquad (14)$$

The transparency condition looks, like in the case of the induced Compton scattering, see Equation (10), as $\tau_{\rm R} \lesssim 10$. This yields the condition for the minimal distance to the high-density region

$$r > 2.2\times 10^9 N_9^{1/4}(S_{\rm Jy}\Delta t_{-3})^{1/2} D_{300}\ {\rm cm}. \qquad (15)$$

One sees that the induced Raman scattering does not place much more severe restriction on the propagation in the outer corona than the induced Compton scattering.

5. CONCLUSIONS

In this paper, we studied the induced scattering of short radio pulses (having in mind FRBs) in stellar coronae. The rate of the induced scattering is highest within and in the vicinity of the source, where the radiation energy density is maximal. Our estimate shows that an FRB could be emitted only if the density in and around the source is as small as

$$N \lesssim 10^5\frac{\Delta t_{-3}}{\lambda_{20}^2 S_{\rm Jy} D_{300}^2}\frac{v_{\rm s}}{c}\ {\rm cm}^{-3}. \qquad (16)$$

This is well below the density $N \sim 10^{8-9}\ {\rm cm}^{-3}$ necessary to provide the dispersion measure observed in FRBs.

Of course the dispersion measure is acquired at distances of $\sim 10^{12-13}$ cm, much larger than the source size; thus, one cannot exclude the possibility that FRBs are generated within very-low-density bubbles, which are formed by some reason in the dense corona. We estimated the induced scattering (both Compton and Raman) at large distances from the source and found that pulses with the parameters of FRBs could propagate through the corona if they meet the dense plasma at distances not less than $\sim 10^9$ cm from the source. Therefore, our final conclusion is that FRBs could be produced in stellar coronae but only if a rather non-trivial density distribution is maintained, at least during the burst.

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