ON THE DETECTABILITY OF PROMPT COHERENT GAMMA-RAY BURST RADIO EMISSION

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ABSTRACT

Both induced Compton scattering and induced Raman scattering strongly limit the observability of the extremely bright (\(\gg 10^{21}\) K), prompt coherent radio emission recently predicted to emanate from gamma-ray bursts (GRBs). Induced Compton scattering is the main limiting factor when the region around the progenitor is not dense but when one still considers the scattering effect of a tenuous circumburst ISM. For a medium of density \(0.01 \eta_{0.01}\) cm\(^{-3}\) and a path length \(L_{\text{circ}}\) kpc and emission that is roughly isotropic in its rest frame, the brightness temperature is limited to \(< 3 \times 10^{10} \Gamma_{10}^{-2} n_{\text{circ}}^{-1} L_{\text{circ}}^{-1} \text{K}\), where \(100 \Gamma_{10}\) is the Lorentz factor of the frame in which the emission occurs. Thus, for a burst at distance \(D\) the predicted emission is only visible if the jet is ultrarelativistic, with \(\Gamma \approx 10^4 (D/100\text{ Mpc})\), or if the intrinsic opening angle of the emission is extremely small. Thus, the presence or absence of such radio emission provides an excellent constraint on the Lorentz factor of the GRB outflow during the very early stages of its outburst. Induced Raman scattering imposes an even more stringent limit independent of the emission opening angle, but only effective if GRB emission must propagate through a dense progenitor wind within \(\sim 10^{15}\) cm from the blast center.

Subject headings: gamma rays: bursts — plasmas — radiation mechanisms: nonthermal — scattering — waves

1. INTRODUCTION

Several mechanisms in which extremely bright coherent radio emission may be generated within \(\sim 10\) s of the initial explosion of a gamma-ray burst (GRB) have recently been proposed (Usov & Katz 2000; Sagiv & Waxman 2002; Moortgat & Kuiper 2005), and a number of strategies are being formulated to detect this radiation. The hypothesized properties of the radiation are within the detectability of several next-generation low-frequency radio arrays, including the Low Frequency Array (Fender et al. 2007) and the dedicated GRB All-Sky Spectrometer Experiment (GASE; Morales et al. 2005).

There are a number of impediments to the detection of prompt radio emission. Dispersion smearing by the intergalactic medium (IGM), in which the signal arrival time is strongly frequency-dependent, has received considerable attention in the context of GRB radio emission (Inoue 2004). However, this effect does not limit the detectability of impulsive emission if the signal can be dedispersed, which is possible if it is observed with sufficiently high spectral resolution. A potentially more serious limitation arises if the IGM is highly inhomogeneous. Multipath propagation through such a medium results in strong temporal smearing of any impulsive signal at low frequencies (Williamson 1972; Lee & Jokipii 1975; Cordes & Lazio 1991). Temporal smearing causes an irreversible loss of sensitivity when the smearing time exceeds the signal duration. Nonetheless, temporal smearing does not currently place any solid constraints on the detectability of bursty low-frequency radio emission because little is known about the level of turbulence in the IGM on the small scales relevant to this effect.

An important property of all proposed mechanisms is that they produce radio emission with brightness temperatures in excess of \(10^{21}\) K. In all cases the emission is generated at low frequencies, must come from a small region if the emission is prompt, and is predicted to possess a flux density in excess of \(\sim 1\) Jy. In this Letter we investigate the effect of induced Compton and induced Raman scattering as this radio emission escapes through either the dense stellar wind of the progenitor or the interstellar medium (ISM) immediately surrounding the source. These propagation effects are potentially far more important than those previously discussed because they strongly alter the properties of radiation with high brightness temperatures \(\gg 10^{20}\) K, rendering it unobservable. It is pertinent to consider Raman scattering in particular because it is the dominant scattering mechanism in similar astrophysical situations involving comparably bright pulsar emission. This mechanism is the favored explanation of eclipses in the binary pulsars PSR 1957+20 and PSR 1744–24A (Eichler 1991; Gedalin & Eichler 1993; Thompson et al. 1994; Melrose 1994; Luo & Melrose 1995), for which the pulsar beams propagate through the stellar winds of their companions at certain orbital phases.

In § 2 we briefly review the physics of induced Compton and Raman scattering and describe the conditions under which they are important. In § 3 we calculate the properties of the scattered radiation and the limits they impose on the detectability of prompt coherent radio GRB emission. The consequences of our findings are summarized in § 4.

2. SCATTERING MECHANISMS

Induced Compton scattering is an important limiting process for bright sources. It substantially enhances the contribution of spontaneous (Thomson) scattering of photons when the brightness temperature of the radiation exceeds \(\sim m_e c^2/\kappa (\Delta \Omega)^2\), where \(\Delta \Omega\) is the solid angle subtended by the radiation beam. Induced Compton scattering limits the brightness temperature to (e.g., Wilson & Rees 1978; Thompson et al. 1994)

\[
T_s \leq \frac{m_e c^2 (\Delta \Omega)^2}{k \tau},
\]

where \(\tau = \int dr \sigma_t n(r)\) is the Thomson optical depth. If the emission is isotropic but the emitting region is approaching at a Lorentz factor \(\Gamma\), one makes the replacement \(\Delta \Omega^2 \rightarrow \Gamma^{-2}\) (Begelman et al. 2005).

Induced Compton scattering is important under a large range of circumstances. It might be supposed that induced Compton scattering is less effective at wavelengths exceeding the plasma
Debye length, $\lambda_D$, because the electric fields of the electrons are screened by other electrons. However, this is exactly compensated by the enhanced scattering caused by clustering of electrons around less mobile electrons (e.g., Thompson et al. 1994). Nonetheless, at such long wavelengths other effects modify the scattering if the brightness temperature of the radiation is sufficiently high, and the most important of these is induced Raman scattering.

Induced Raman scattering refers to the process in which a beam of bright electromagnetic radiation propagating through a plasma induces an instability, creating turbulent Langmuir waves (plasmons) in the plasma that subsequently scatters the beam. Raman scattering does not limit the brightness temperature in the same manner as induced Compton scattering. When Raman scattering is effective, the region in which the scattering occurs acts like a secondary photosphere, so that any beamed radiation is made isotropic, and a pulse of radiation is smeared over a timescale larger than the light-travel time across the Raman photosphere (see Levinson & Blandford 1995). Raman scattering produces relatively small frequency shifts, $\Delta \nu \omega \sim (kT/\mu e c^2)^{1/2}$, for nonrelativistic ambient plasma temperatures, $T$, so the total radio spectrum is not strongly altered.

Raman scattering is important, provided that several conditions are met. The first is that Landau damping does not prevent propagation of the Langmuir waves. This implies that only plasma turbulence with wavevectors $k < q_L = 0.27\lambda_D^2$ can propagate and are available to scatter the radiation. Landau damping prevents backscattering for frequencies

$$\nu > \nu_L = 90n_b^{1/2}T_b^{1/2} \text{ MHz}$$

and limits the maximum scattering angle to

$$\theta_{\text{max}} \sim \frac{2\nu_L}{\nu}, \quad \nu \gg \nu_L.$$  

The second condition relates to the level at which the turbulence saturates. This is determined by whether the plasmon occupation number saturates due to linear or nonlinear damping, giving rise to weak or strong scattering, respectively. We concentrate on the strong scattering limit applicable to the high brightness temperatures expected of coherent GRB emission. In this regime the plasmon energy density grows exponentially with time until the production rate balances the growth rate. This occurs when the photon occupation number, $N_p = kT_p/\hbar \omega$, exceeds

$$N_p > N_r = \left[ \frac{3n_e \sigma_T \omega}{8\pi^2 \gamma_e (\hbar \omega^3 / m_e c^2)} \right] (1 + \cos^2 \theta)^{-1}$$

(Thompson et al. 1994), where $\Gamma_{\nu, 0} = 32n_e T_b^{-3/2} \text{s^{-1}}$ is the electron-ion collisional damping rate and $\theta$ is the angle through which the radiation is scattered. An additional constraint is that the Landmuir turbulence growth timescale must be much shorter than the duration of the prompt emission. The growth time depends on the ratio of the critical flux density, $S_r$, implied by equation (4) to the beam flux density, $S_{\nu, 0}$, and is given by $\sim S_r/2S_{\nu, 0} \Gamma_{\nu, 0} = 0.0156n_e^{-1}T_b^{1/2} (S_r/\nu_{\nu, 0}) \text{ s}$. This growth time is much smaller than 1 s for bright emission that exceeds the critical flux density and conditions typical of a plasma in which induced Raman scattering is effective.

The extension of Raman scattering to magnetized plasmas with thermal effects is treated by Luo & Melrose (1995), who show that the dominant effect of large-angle scattering is from Bernstein waves. Bernstein waves propagate nearly perpendicular to the magnetic field near harmonics of the electron cyclotron frequency and possess sufficiently large wavenumbers to permit large-angle scattering and backscattering. This generalization is important only in the regime in which the condition $\Omega_p < \omega_p$, i.e.,

$$1.8 \times 10^4 \left( \frac{B}{1 \text{ mG}} \right) \ll 5.6 \times 10^4 \left( \frac{n_e}{1 \text{ cm}^{-3}} \right)^{1/2},$$  

is violated; otherwise only the Langmuir waves dominate the scattering. For most cases of interest the role of the magnetic field is unimportant, so the description of Raman scattering given above is sufficient; indeed, the condition $\Omega_p < \omega_p$ is an essential element of the Sagiv & Waxman (2002) model.

Brillouin scattering, the scattering of nonisotropic radiation by ion or electron acoustic waves, can also limit the radiation properties, but this is less effective than Raman scattering when the electron temperature exceeds the ion temperature (e.g., Luo & Chian 1997). Brillouin scattering is therefore unlikely to be important here and its effect is not considered. However, we do note that ion acoustic waves may enhance the efficiency of induced Raman scattering (Chian & Rizzato 1994) by coupling to Langmuir waves.

In systems in which conditions for both stimulated Compton and Raman scattering are favorable, the latter is the dominant process (see Thompson et al. 1994; Levinson & Blandford 1995). This is because the induced Compton scattering rate is significant only if the propagation direction of the scattered photon lies inside the radio beam. The same condition does not apply to Raman scattering. Much larger recoil angles are possible in stimulated Raman scattering, only being limited by Landau damping or the wavenumber up to which the Langmuir turbulence extends.

Induced Compton scattering is relevant to bright emission from both active galactic nuclei (AGNs) and pulsars (Coppi et al. 1993; Begelman et al. 2005; Wilson & Rees 1978). Induced Raman scattering is also discussed extensively in relation to eclipsing binary pulsars and constraints on coherent emission from AGNs (Gedalin & Eichler 1993; Thompson et al. 1994; Levinson & Blandford 1995). The fact that extremely bright radiation is observed in pulsars implies that they must possess highly relativistic winds that mitigate the effects of scattering. In the case of the Crab pulsar the absence of induced Compton scattering implies a wind with a minimum Lorentz factor of $\sim 10^4$ (Wilson & Rees 1978), while induced Raman scattering imposes a similar limit of $\gg 8 \times 10^2$ (Luo & Melrose 1994).

3. LIMITS ON PROMPT GRB RADIO EMISSION

The limiting role played by scattering in a GRB environment depends on the properties of the medium that the bright emission must propagate through. Two circumburst medium models that encompass the range of properties likely to be encountered are considered. These also correspond closely to those considered for the generation of the coherent emission in the first place (see Sagiv & Waxman 2002). The first model is relevant to a burst from a system whose progenitor is a massive star, in which case the emission must propagate through the relic stellar wind. Such winds are thought to have characteristic velocities of order $10^3 \text{ km s}^{-1}$ and mass-loss rates $M \sim 10^{-5} M_\odot \text{ yr}^{-1}$ (Chevalier & Li 1999),
with temperatures $T \sim 10^4$ K. For an isotropic outflow the electron density at radius $r$ is

$$n_e = 3.0 \times 10^{11} \left( \frac{M}{10^{-5} M_{\odot} \text{ yr}^{-1}} \right) \times \left( \frac{v}{10^3 \text{ km s}^{-1}} \right)^{-1} \left( \frac{r}{10^{12} \text{ cm}} \right)^{-2} \text{ cm}^{-3}. \quad (6)$$

The parameters of the second model are relevant to bursts resulting from mergers (e.g., neuron star–neutron star mergers), where the system has evacuated a cavity and the only available scattering material is the ionized ISM. This plausibly has a density in the range $n_e \sim 0.001–1 \text{ cm}^{-3}$ and a temperature $T \sim 10^4$ K, corresponding to that of the warm ionized medium of our Galaxy. The low end of the density range is appropriate to a burst that occurs in an elliptical galaxy or on the outskirts of its host galaxy, as appears to be relevant to short-duration GRBs (Prochaska et al. 2006; Berger et al. 2006).

The effectiveness of the scattering mechanisms also depends on the properties of the incident radiation. The detailed properties of the emission vary according to the radiation mechanism invoked. Sagiv & Waxman (2002) propose synchrotron maser emission from a purely relativistic, weakly magnetized plasma in which the plasma frequency greatly exceeds the electron cyclotron frequency. The emission is expected to occur on a timescale of a minute after the initial gamma-ray burst at frequencies in the range ~3.5–200 MHz, depending on the density of the medium that the blast wave expands into. This model is expected to produce emission as strong as $S_c \sim 1$ Jy for low-redshift bursts (see Inoue 2004). This corresponds to a $T_b = 10^{23}–10^{25}$ K, assuming a source size $\theta \sim \Gamma \Delta \Delta \Delta$.

A mechanism advanced by Usov & Katz (2000) involves bursty synchrotron emission generated in the fields of low-frequency waves ahead of the GRB shock front. This emission is expected to occur predominantly below ~30 MHz and to last 1–10$^3$ s. Emission generated via this mechanism is predicted to possess a flux density $\sim 2 \times 10^9 \epsilon_b^{3/2}$ Jy, where $10^{-4} \leq \epsilon_b < 1$ is the fraction of the wind power remaining in the magnetic field at the radius at which the blast wind begins decelerating due to its interaction with ambient gas. The associated brightness temperature is $T_b = 10^{24}–10^{29}$ K.

Moortgat & Kuijpers (2005) advance a more indirect mechanism for the generation of low-frequency emission from coalescing systems. They propose that gravitational radiation from the system excites MHD wave modes at kilohertz frequencies, which in turn undergo inverse Compton scattering off relativistic material in the GRB outflow. Inverse Compton scattering on particles with $\gamma > 100$ boosts the radiation to observable (~100 MHz) frequencies. This radiation is also predicted to be extremely bright: a source at 1 Gpc is expected to be visible as a $2 \times 10^{19}$ Jy pulse of duration ~3 minutes with a bandwidth ~30 MHz, corresponding to $T_b \sim 10^{29}$ K.

As all three mechanisms generate extremely bright emission, both induced Compton and Raman scattering are expected to be important limiting process outside the emission region.

### 3.1. Induced Compton Scattering

We first consider the limits imposed by induced Compton scattering. If the radiation is emitted isotropically in the rest frame of the emitting plasma, the opening angle is determined only by the Lorentz factor of the frame in which the emission occurs. For material propagating through the wind of a massive progenitor with inner radius $r_i$, the brightness temperature is constrained to be

$$T_b \leq 3.0 \times 10^{22} \left( \frac{r_i}{10^5 \text{ cm}} \right) \left( \frac{\Gamma}{100} \right)^2 \times \left( \frac{M}{10^{-5} M_{\odot} \text{ yr}^{-1}} \right)^{-1} \text{ K}. \quad (7)$$

One can also estimate the effect of scattering associated with the propagation of the radiation through the ISM surrounding the burst. The limit imposed by induced Compton scattering after propagation through a medium of density $n_e$ and length $L$ in the ISM is

$$T_b \leq 2.9 \times 10^{18} \left( \frac{\Gamma}{100} \right)^2 \left( \frac{n_e}{0.01 \text{ cm}^{-3}} \right)^{-1} \left( \frac{L}{1 \text{ kpc}} \right)^{-1} \text{ K}. \quad (8)$$

which can be even more stringent than that imposed by circumburst material. If the radiation is not isotropic in the rest frame but is instead confined to a narrow solid angle, the emission opening angle is less than $\theta \sim \Gamma \Delta \Delta \Delta$. Instead, GRB observers have observed intrinsic beam angular sizes of order $\theta \sim 10^{-2}$.

Consider the effect of these limits on the observability of the various proposed radio emission mechanisms. For emission of duration $\Delta t$ at a luminosity distance $D_L$, the angular size is of order $\theta \sim 10^{-2} \Delta t/D_L$, so the maximum permitted flux density is

$$S_c \approx 2.6 \left( 1 + z \right)^2 \left( \frac{T_b}{10^{20} \text{ K}} \right) \left( \frac{\nu}{30 \text{ MHz}} \right)^2 \times \left( \frac{\Delta t}{100 \text{ s}} \right)^2 \left( \frac{\Gamma}{100} \right)^2 \left( \frac{D_L}{100 \text{ Mpc}} \right)^{-2} \text{ mJy}. \quad (9)$$

The above brightness temperature limits are well below those predicted for all three proposed radiation mechanisms. The brightness temperature constraint imposed by propagation through the surrounding ISM indicates that prompt GRB emission is so heavily suppressed by induced Compton scattering as to be unobservable unless the observing frequency exceeds ~300 MHz or the Lorentz factor exceeds 10$^3$.

If the emission is to evade induced Compton scattering, it must be intrinsically emitted into a narrow angle, $\Delta \Omega < 1$, in its rest frame. For the fiducial ISM properties used in equations (7) and (8), induced Compton scattering is evaded if the intrinsic emission angle is less than $\sim 5 \times 10^{-2} (T_b/10^{25}$ K $)^{-1/2}$ sr. Instead, GRB models suggest large jet opening angles, ~0.1 (e.g., Frail et al. 2001), suggesting that scattering is unlikely to be effective. Moreover, even if the emission opening angle is narrow, the radiation may still be affected by induced Raman scattering, which scatters emission from narrow beams sources effectively.

### 3.2. Induced Raman Scattering

For the temperatures and densities characteristic of the ISM, Landau damping is effective and prevents induced Raman scattering at frequencies above ~1 MHz. Scattering is effective, however, if the region immediately surrounding the GRB is
if the radiation is emitted within the radius $r_p$. Material within this radius and its flux density exceeds a critical in situ value $S_{\text{crit}}$, determined by equation (4), which corresponds to an observed flux density of

$$S_{\text{crit}} = 0.68(1 + z)(1 + \cos^2 \theta)^{-1} \left( \frac{n_e}{10^5 \, \text{cm}^{-3}} \right)^{1/2} \left( \frac{D_L}{20 \, \text{Mpc}} \right)^{-2} \left( \frac{r_0}{10^{15} \, \text{cm}} \right)^2 \left( \frac{T_e}{10^6 \, \text{K}} \right)^{-3/2} \left( \frac{\nu}{30 \, \text{MHz}} \right)^{-1} \text{mJy.}$$  

(10)

Raman scattering thus limits the radiation properties effectively if the radiation is emitted within the radius $r_p$. Material within this radius acts as a “Raman photosphere,” in which strong scattering through $\sim \pi/2$ is possible. Scattering isotropizes any initially beamed radiation over all 4$\pi$ sr and lowers the brightness temperature of the radiation as it now appears to emanate from a region of size $r_p$. This has the advantage of rendering the prompt emission from any bursts not beamed toward an observer visible.

However, the associated disadvantage is that any temporal signature in the emission is smeared over a timescale $\approx r_p/c \sim 10$ hr, thus destroying a key observational signature of the bright, initially short-duration, emission.

However, induced Raman scattering may be evaded if the emission does not occur within the radius $r_p$. This caveat is particularly important for the gravitational wave (GW)–plasma coupling mechanism proposed by Moortgat & Kuijpers (2005), where the radii over which favorable coupling could conceivably occur at large distances from the GW production site.

4. CONCLUSIONS

Stimulated scattering substantially impedes the propagation of the bright coherent radio emission predicted to occur within the first 10–60 s of gamma-ray bursts. These effects limit the radio emission to brightness temperatures several orders of magnitude below those predicted to be intrinsic to the emission mechanisms themselves. The limiting effects of induced Compton scattering are only evaded if the emission is intrinsically emitted into a narrow cone or if the bulk Lorentz factor of the material in which the emission occurs is extremely high, with $\Gamma \gtrsim 10^5 (D/100 \, \text{Mpc})$. Thus, the presence or absence of such radio emission provides an excellent constraint on the maximum Lorentz factors encountered in the GRB outflow during the very early stages of its outburst. This limit exceeds present lower limits on the Lorentz factor, $\Gamma \gtrsim 100–400$, imposed by the apparent absence of photon-photon pair production and Compton scattering of photons off the pair-produced $e^\pm$ (Lithwick & Sari 2001).

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