A Plasma Instability Theory of Gamma-Ray Burst Emission

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Abstract.
A new theory for gamma-ray burst radiation is presented. In this theory, magnetic fields and relativistic electrons are created through plasma processes arising as a relativistic shell passes through the interstellar medium. The gamma-rays are produced through synchrotron self-Compton emission. It is found that shocks do not arise in this theory, and that efficient gamma-ray emission only occurs for a high Lorentz factor and a high-density interstellar medium. The former explains the absence of gamma-ray bursts with thermal spectra. The latter provides the Compton attenuation theory with an explanation of why the interstellar medium density is always high. The theory predicts the existence of a class of extragalactic optical transient that emit no gamma-rays.

1. Introduction

A plasma instability theory for the prompt emission of gamma-ray bursts is presented.[5] In this theory, a relativistic shell with $\Gamma \gg 1$ passes through the interstellar medium. Two plasma instabilities, the filamentation instability and the two-stream instability, generate a magnetic field and heat the electrons to relativistic energies. The heated electrons emit synchrotron radiation in the radio to optical bands and synchrotron self-Compton radiation from the optical to gamma-ray bands.

This theory produces the observed prompt gamma-ray emission seen in all bursts, and the prompt optical emission seen in GRB 990123. The magnetic field generated by the filamentation instability is calculated from first principles. Lower limits on $\Gamma$ and $n_{ism}$ arise from the requirement that the model efficiently radiate gamma-rays. The limit on density requires each gamma-ray burst to be surrounded by a medium that is optically thick to Compton attenuation. The limit on $\Gamma$ suggests that there exists a class of transient that produces optical and ultraviolet emission but no gamma-ray emission.

One of the more interesting aspects of the theory is that the plasma instabilities cannot satisfy the Rankine-Hugoniot conditions, so a shock is not produced by these instabilities. As a consequence, the interstellar medium remains in place after passage of the relativistic shell. This permits the interstellar medium to interact with multiple relativistic shells to produce the complex time structure seen in gamma-ray burst light profiles.
2. Plasma Instabilities

Two instabilities arise when a plasma streams through a second plasma at a highly relativistic velocity. The first is the filamentation instability, while the second is the two-stream instability.[6] Of these, the former has the higher growth rate.

The growth rate of the filamentation instability as measured in the shell rest frame is

$$\gamma_f' \approx \frac{1}{2} \sqrt{\frac{4\pi e^2}{m_e n_{ism}}} ,$$  \hspace{1cm} (1)

where \(n_{ism}\) is the number density of the interstellar medium in the ISM rest frame, and \(m\) is the mass of the filamenting plasma component of the ISM. The filamentation occurs for wave numbers perpendicular to the velocity vector that obey the inequality

$$k_\perp > \omega_{p,e,shell}/c .$$  \hspace{1cm} (2)

In other words, the length scale of the filamentation is set by the electron plasma frequency of the shell as measured in the rest frame of the shell.

The filament is a magnetic pinch, with a toroidal magnetic field that is formed when the particles in the filament collapse to the center of the filament. The filament grows until its growth rate equals the bounce frequency of a particle across the magnetic pinch. This saturation defines the maximum magnetic field that can be generated.[7, 8]

For both ions and electrons, the maximum field strength is the same

$$B' = \frac{m_e c^2 n_{ism}^2 \Gamma^2}{16 \pi n_{shell}'} .$$  \hspace{1cm} (3)

One finds that for \(n_{shell}'/n_{ism} = \Gamma\), which is a natural value for the efficient emission of radiation, the magnetic field is \(B' = 0.14 \text{ G}\) when \(\Gamma = 10^3\) and \(n_{ism} = 1 \text{ cm}^{-3}\), and \(B' = 45.4 \text{ G}\) when \(\Gamma = 10^5\) and \(n_{ism} = 10^5 \text{ cm}^{-3}\). The energy extracted from the interstellar medium and converted into magnetic and thermal energy is small. This is shown in Figure 1. As a consequence, even when the Rankine-Hugoniot condition on \(n_{shell}'/n_{ism} = \Gamma\) is satisfied, the fraction of kinetic energy that is converted to thermal and magnetic energy is tiny, so that the interstellar medium continues to stream through the shell.

The two-stream instability acts on the electrons to bring them into an equilibrium with the two ion streams. This instability grows at the rate of

$$\gamma_{2s}' \approx \frac{1}{2} \sqrt{\frac{4\pi e^2}{m_e n_{ism}}} \Gamma^{-1} .$$  \hspace{1cm} (4)

The growth rate of the electron two-stream instability is smaller than the ion filamentation instability by the factor of \(m_p^{1/2}/m_e^{1/2} \approx 0.04\). The two stream instability will grow until the electron Lorentz factor is of order \(\Gamma\). At this point, the system becomes stable. This instability therefore only converts \(m_e/m_p\) of the total energy of the interstellar medium into thermal energy.

3. Radiative Mechanisms

The two radiative mechanisms at work in this theory are synchrotron emission and synchrotron self-Compton emission. The characteristic energy of each process is given
Figure 1. Fraction of energy that goes into magnetic field and ion thermalization through the filamentation instability. This is measured in the rest frame of the shell. The energy available is the energy of the interstellar medium streaming through the shell. The curves are plotted as the ratio $n_{ism}/n_{shell}'. The solid curve gives the fraction of energy in magnetic field. This fraction is independent of $\Gamma$. The dotted curve gives the fraction of energy that goes into ion thermal energy. The upper curve is for $\Gamma = 10^4$, while the lower is for $\Gamma = 10^3$. The squares mark the value of $\eta$ that one expects from the Rankine-Hugoniot relations for $\Gamma = 10^3$, while the diamonds mark this relation for $\Gamma = 10^4$.

in Figures 2 and 3 for $n_{ism} = 1 \text{ cm}^{-3}$ and $n_{ism} = 10^5 \text{ cm}^{-3}$. This characteristic energy defines the maximum energy of the continuum as defined by the maximum energy of the electron distribution. The minimum energy of the synchrotron emission is given by the cyclotron energy, which is

$$\nu = 2.68 \times 10^8 \text{ Hz} \frac{n_{ism}^{3/2}}{\Gamma_3^2},$$

where $\Gamma_3 = \Gamma/10^3$. This value is smaller than the characteristic synchrotron energy by the factor of $\Gamma^2$.

The synchrotron self-Compton energy range is determined by a single scattering, since more than one scattering takes the photons to the characteristic electron energy. The minimum energy is set by $\Gamma^2$ times the cyclotron resonance energy, so that the low end of the synchrotron self-Compton continuum overlaps the high end of the synchrotron continuum. The characteristic Compton scattering energy is a factor of $\Gamma^2$ larger than this. From the figures, one sees that for $\Gamma > 10^3$, the energy range of the Compton scattered radiation extends above 1MeV. For a lower value of $\Gamma$, the
Figure 2. Characteristic observed photon energies for $n_{ISM} = 1 \text{ cm}^{-3}$. The solid curves give characteristic energies for single scattering synchrotron self-Compton emission. The dotted curves are for synchrotron emission. The upper pair are for $\Gamma = 10^4$, while the lower pair are for $\Gamma = 10^3$. Note that each of these curves peak at $\eta \approx \Gamma^{-1}$. Only the synchrotron self-Compton emission is capable of producing gamma-ray emission.

4. Selection Effects

The emission of gamma-rays defines one selection effect. In order to produce gamma-rays, $\Gamma > 10^3$. This provides an explanation for the absence of photon-photon pair creation in gamma-ray bursts, as demonstrated by the absence of gamma-ray bursts with thermal spectra.

A second selection effect that comes into play in this theory concerns the efficient production of gamma-rays. If the density is too low, the rate of radiative cooling is far below the rate at which electrons are thermalized. Such bursts would be dim relative to their high-density counterparts. The most observable bursts are therefore those with a sufficiently high $n_{ism}$ to efficiently convert electron thermal energy into cooling occurs predominately at optical and ultraviolet wavelengths. Because gamma-ray bursts are identified by their gamma-ray emission, bursts with $\Gamma < 10^3$ will not be observed. This suggests that there exists a class of burst phenomena with optical and ultraviolet emission, but no gamma-ray emission.
gamma-rays. This lower limit on $n_{ism}$ can be written as

$$n_{ism} > 8.22 \times 10^4 \text{cm}^{-3} \mathcal{M}_{27}^{-\frac{1}{3}} \Gamma_{3}^{-\frac{12}{3}} f_{\text{emis}} \left(\frac{R}{R_0}\right)^{\frac{3}{2}}$$

(6)

where $f_{\text{emis}}$ is the fraction of electrons at the characteristic energy, where $R/R_0 \approx (m_p/m_e)^{1/3}$ is the distance traveled when $\Gamma$ drops by a factor of 2 relative to the distance traveled when the ISM is swept up, all under the assumption that the heating of the electrons represent the maximum energy loss, and where $\mathcal{M}_{27}$ is the mass of the shell per unit ster radian in units of $10^{27}$ gm.

The limit given by this last equation is plotted in Figure 4 as a solid line. A similar curve that gives emission that is 10% effective at radiating the energy converted into thermal energy is plotted as a dotted line. The importance of this limit is that the gamma-ray burst mechanism requires a high density interstellar medium to operate efficiently. When the burst radiates efficiently, the interstellar medium is of sufficient density to attenuate the gamma-ray spectrum through Compton scattering.[2] This provides the plasma instability theory with a mechanism that gives the spectrum a characteristic energy of several hundred keV, despite the broad spectral range of the synchrotron self-Compton continuum, and its strong dependence on $\Gamma$. Such a mechanism is required to correctly reproduce the observed spectra.[3, 4]
5. Discussion

The plasma instability theory discussed above is a new mechanism to produce prompt gamma-ray burst emission. It has several unique features.

- The plasma instability theory produces the prompt gamma-ray emission without creating a shock. This implies that additional gamma-ray bursts can occur in the interstellar medium when new relativistic shells are ejected by the source, because the region is not cleared of material.
- The requirement that the mechanism efficiently produce gamma-rays introduces selection effects, so that bursts have \( \Gamma > 10^3 \) and \( n_{ism} > 10^5 \text{cm}^{-3} \).
- There exists a class of optical transient that has no gamma-ray emission. These bursts differ from gamma-ray bursts in having \( \Gamma < 10^3 \).
- The lower limit on \( n_{ism} \) ensures that gamma-ray bursts are always in region in which Compton attenuation by the surrounding interstellar medium occurs.
The next step in developing this theory is to undertake a numerical study of the plasma instabilities. The goal of the study will be to confirm the analytic results discussed above, and to provide a precise calculation of the electron distribution produced by the instabilities. A second aspect of the theory that will be examined is the afterglow radiation produced in this theory; the cooling of the region behind the relativistic shells gives a light curve that differs from the light curve created by the decelerating shell, adding a complexity to the afterglow from this theory that is not present in the shock theories of afterglow radiation. Finally, calculations of model spectra and their comparison to observed spectra is will be undertaken. In particular, a comparison of the optical and gamma-ray spectrum of this model to that of GRB 990123[1] is planned. This study will test whether the prompt optical and gamma-ray emission are part of a single synchrotron self-Compton continuum.

References