Understanding prompt emission: Where do we stand?

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In recent years, there is a renewed debate about the origin of the observed prompt emission signal. Some authors found that synchrotron emission can dominate the spectra of several long bursts, and a recent analysis show that it may be possible to overcome the famous 'line of death' argument by a direct fitting procedure. On the other hand, several recent works showed that non-dissipative photosphere is preferred as the dominant emission model in at least 1/4 of long and 1/3 of short GRB population. Here I critically review the arguments given as well as their physical consequences. I present some recent results that show a connection between the prompt spectra and the early afterglow emission, thereby argue for an independent method of discriminating the physical conditions that result in the different dominant radiative processes.

Keywords: Gamma-ray: bursts; Radiative mechanisms: non-thermal; photosphere; polarization

1. Introduction

After more than three decades of an extensive study, there is a broad consensus about many of the observational properties defining gamma-ray bursts (GRBs), yet there is still a strong debate about the correct way of interpreting the data. One of the key problems is that when interpreting the observed data, one may conclude about the leading radiative process that produces the observed signal. However, the radiative process is the last in a long chain of physical processes, that include gravitational energy extraction, relativistic motion, kinetic energy dissipation, particle acceleration and radiative process that eventually result in the observed signal. It is therefore impossible to disentangle the radiative process from the rest of this chain. Furthermore, the underlying physics of most of these processes is still only partially understood, and is the subject of an intensive research. As a result of this complexity, the leading radiative process is still uncertain.

When looking at the data, common to all GRBs are the following. The spectra has a peak in the sub-MeV range; at lower energies (below this peak) the spectral slopes are steep, $F_\nu \propto \nu^\alpha$, with $\alpha \approx 0$, but with considerable variation between bursts, and sensitive to the fitting procedure; In several bursts a higher energy emission, at the GeV-TeV range is seen; and when making spectral fittings for bursts with strong enough signal, multiple components are identified.[1]

The lightcurve of the prompt emission, which lasts for a few- few tens of seconds generally varies at a sub-second level. The prompt phase itself is distinguished from later emission ("afterglow") by a sharp decay in the flux. In a large fraction - 10's of % of GRBs, an X-ray plateau is detected, lasting for a few thousands seconds following the prompt phase. At later phase, a decaying "afterglow" which is well modeled by a self-similar expansion phase (the "Blandford-McKee" solution) is frequently detected. Furthermore, to many nearby long GRBs, evidence for a coinciding supernovae explosion exist. Finally, the connection between GRB170817 and the gravitational wave (GW) event clearly indicates that this particular event is associated with the merger of binary neutron stars.[2]

Following these plethora of data, already in the early 1990's the basic "fireball" picture had emerged,[3–6] according to which the gravitational energy released during the collapse of a massive star (or merger of binaries) is partially converted to kinetic energy in the form of a relativistic jet. At a second stage, part of this kinetic energy is released by internal dissipation (e.g., shock waves). Part of this energy is used in a accelerating particles, which then emit the observed signal. This model could explain both the high energy ($>$ MeV) emission, which is above the threshold for pair production, as well as the high variability detected in the lightcurve. It further obtained the afterglow as a prediction, to be later confirmed after the launch of the Beppo-SAX satellite.

Despite this success, many of the basic questions remain unanswered in the framework of this model. These include: (i) the nature of the progenitor star, and the event that led to its explosion and death; (ii) the nature of the launching mechanism of the relativistic jet[7,8]; (iii) The composition of the jet, and in particular its magnetization; (iv) The structure (geometry), dynamics (velocity field) and evolution of the propagating jet; (v) The nature of the kinetic energy dissipation mechanism - while initially internal shocks were considered, it became evident that they are not very efficient energy converters,[9] and additional mechanisms were proposed, mainly involving strong magnetic fields[10,11]; This directly related to the question of particle acceleration, which is associated with this dissipation. (vi) The nature of the radiative processes involved in producing the observed signal. (vii) Addressing these questions is important in understanding the connection of GRBs to other objects of interest and field of active research, such as stellar evolution, star formation, pop-III stars, supernovae, binary star evolution, cosmic rays, energetic neutrinos, and more. Finally, complete understanding of the nature of GRBs could be useful for addressing fundamental questions in cosmology (e.g., about the expansion of the universe) and Lorentz violation.

The key problem remains that while many theories exist for each of these open questions, in order to test the theoretical ideas one has to rely on the observed signal, which is the result of the long chain of physical processes. Thus, one has to find clever ways of discriminating between the models based on the final outcome, which is not directly related to the processes themselves, and in many cases is very confusing.

2. The leading radiative processes

Very broadly speaking, there are three competing models that are in wide use in explaining the observed prompt emission signal. These are synchrotron as a leading radiative process, hadronic and photospheric model.

The idea that synchrotron emission (possibly accompanied by inverse-Compton [IC] scattering at higher energies) is the leading radiative process during the prompt phase of GRBs was in wide use in the 1990's,[12,13] and regain interest in recent years.[14–16] Synchrotron emission is indeed very ubiquitous in many different astronomical objects, and in many GRBs it provides very good fitting to the lightcurve and spectra seen during the afterglow phase. Indeed, it is a very efficient way of extracting energy from energetic electrons via radiation. Furthermore, the conditions for this process to occur, namely the existence of energetic electrons and a magnetic field are both believed to exist as part of the dissipation process of the relativistic jet's kinetic energy. This is despite the fact that a complete model for the dissipation process still does not exist.

A second possibility that had been discussed is that of a hadronic origin, namely that the observed signal is due to emission from energetic protons, e.g., via synchrotron emission,[17] or possibly photo-meson (pion production) or Bethe-Heitler (pair production) interaction of the protons with the ambient photon field. In order for this process to take place, existence of energetic protons and a magnetic field are required. While synchrotron emission from protons is considerably less efficient than emission from the electrons due to the smaller cross-section, the advantage is that observations of energetic cosmic rays provide a direct evidence that proton acceleration to high energies necessarily exist in astronomical objects, while evidence for acceleration of electrons exist only indirectly. Thus, as long as the theoretical understanding of particle acceleration is incomplete, we do have certainty that this process does exist, though of course it is not clear whether the conditions that exist during GRB prompt emission are sufficient.

The third radiative process discussed is emission from the photosphere.[18] As opposed to the previous alternatives, this can be considered as a more complete model. As part of the GRB "fireball" model, the flow begins its relativistic expansion while being optically thick. Thus, at a certain radius, it must become optically thin - this is the photospheric radius, where photons escape. Thus, a photospheric component naturally exists in expanding, (initially) optically-thick flows, and in particular as part of the GRB "fireball" model. Furthermore, as no additional kinetic energy dissipation is required, this process can be highly efficient, with 10s of % of energy being released as photons at the photosphere.[19–21] On the other hand, in order to gain high efficiency, one requires to avoid adiabatic losses, namely that the photospheric radius r_{ph} is not much above the coasting radius, which marks the end of the acceleration of the jetted material.

3. Confronting synchrotron emission with the data

Already in the 1990's, synchrotron emission was suggested as a leading radiative model to explain the prompt emission from GRBs. This is based on the fact that for relativistic expansion with $\Gamma \gtrsim 100$ and dissipated kinetic energy that is spread roughly equally between accelerating electrons and generating magnetic fields (i.e., equipartition), the observed peak energy, $\nu_m^{ob.} \sim 500$ KeV is in good agreement with the peak observed energy.

However, a closer look reveals that under such a strong magnetic field, the electrons will rapidly cool (namely, will be in the "fast cooling" regime), in which case the expected low energy spectral slope is much shallower than the observed one. This is the famous "synchrotron line of death" problem,[22] which made this model less appealing for many years.

In recent years, as the quality of data increased, several attempts were made to overcome this problem. For example, Refs.[14,15,23] argue that the low energy spectral slope (below the peak) cannot be considered as a single power low, but rather there is an intermediate break at several tens of keV. This break enables to fit the spectra with a smaller than equipartition value of the magnetic field, thereby relaxing the 'line of death' restriction. Recently, Ref.[16] correctly argued that one should not attempt to fit the synchrotron spectra to the already fitted "Band" function, as is commonly the case, but rather directly to the raw data. When doing so, they managed to provide acceptable fits to the data within the framework of the synchrotron emission model.

Despite this success, a close look reveals that in providing these fits, the magnetic field assumed was extremely weak, ~ 1 G, and the emission radius obtained from the fit was $\sim 10^{17}$ cm. These require a ratio of burst energy to ambient density of $E_{53}/n_0 \sim 10^8$, which is 8 orders of magnitude larger than inferred from afterglow data (here and below, $Q_x = Q/10^x$). Thus, while the shape of the spectra can be fitted with such a model, the values of parameters obtained make it physically unacceptable.

Similarly, the idea of synchrotron emission from protons was investigated by several authors.[17,24] The allowed parameter space in this scenario, $B \sim 10^6$ G and emission radius of $R \sim 10^{13}$ cm, are much in line with the parameter estimate from afterglow data. However, due to the much less efficient radiative energy extraction from the protons (as compared to the electrons), this scenario requires that the total amount of energy given to the accelerated protons, E_p exceeds the jet kinetic energy, namely $E_p > E_k$. Thus, this scenario challenges models of particle acceleration.

4. Confronting photospheric emission with the data

The drawbacks of the synchrotron model mentioned above, led several authors to consider photospheric emission as an alternative.[18,19,25] However, this alternative was less appealing for many years, due to the fact that the observed spectra never appears as a "pure black body" (Planck), but rather is much broader.

This situation changes with the observation of GRB090902B.[26] This was a particularly bright burst, which showed clear evidence for a dominant narrow peak, Planck-like component. Furthermore, its extreme brightness enabled a time-resolved analysis during the onset of the prompt phase. This analysis proved that the spectrum change during the prompt phase: it started as a very narrow peak, close to a black body, and then gradually widened to resemble the common "Band" spectra. This had demonstrated the importance of **time-resolved** analysis, as an essential tool needed to understand the origin of the prompt phase.[27]

Recently, a similar analysis done on a large number of bursts[28] showed that this behavior is in fact common among pulses seen in many bright GRBs: initially, many pulses are narrow (hard spectrum) which become softer in time. This may be interpreted as a change in the leading radiative process with time: an initial thermal (or quasi-thermal) emission decays, and a later synchrotron emission becomes dominate at later times.

Furthermore, theoretical works[29–31] proved that in fact the initial expectation for a "Planck" spectrum was misleading: due to light aberration from the relativistically expanding jet, even a "pure" photospheric emission (so called "non-dissipative photosphere", or NDP) would be detected as a broader spectra, with spectral slope $dN/dE \propto E^{-\alpha}$ and $\alpha \approx 0.4$ below the peak[30] (compare with the Rayleigh-Jeans slope of $\alpha = 1$). Even this, though, is an asymptotic limit: when considering the finite detector's energy range, and the "curvature" of the spectrum near the energy peak, it is found that the expected observed values of the low energy spectral slope are even smaller than this.[32]

After considering these effects, a recent analysis show that in fact more than 1/4 of long GRBs, and 1/3 of short GRBs are consistent with having a pure thermal origin.[33,34] When adding a possible sub-photospheric energy dissipation that can potentially broaden the spectra, these fraction of course becomes much larger.

5. Applications

The realization that a photospheric emission does not appear as a textbook-solution blackbody, but rather is modified, enabled a refined analysis of the GRB properties. For example, Ref.[34] showed that the short GRB population that are consistent with having a pure thermal origin can be divided into two separate populations, clearly divided by their peak energy, E_{pk}, duration (T_{90}) and inferred Lorentz factor. One of these populations forms a continuation of the properties of the long GRB population, while the other one is separated. This result thus suggests that the classical separation of the GRB population to "long" and "short", which is based nearly entirely on the duration (T_{90}) is likely insufficient, and additional criteria are needed. Part of the "short" GRB population is in fact a continuation of the long GRB population.

One of the most puzzling questions is the observed isotropic energy-peak energy ("Amati") or luminosity - peak energy ("Yonetoku") relations reported. One appealing advantage of the photospheric emission model is that it may provide a natural explanation to the observed correlation, as due to viewing angle effect. Observers at different angles see the photons with different Doppler shifts, as $\nu^{ob.} = D\nu'$ (here, $D = [\Gamma(1-\beta\cos\theta)]^{-1}$ is the Doppler shift, and primed quantities are in the comoving frame). Using the invariance of L'/ν^2, the observed luminosity is related to the peak energy via $L^{ob.} \propto (\nu^{ob.})^2 \sim E_{pk}^2$, providing a natural explanation to the Yonetoku relation.[35]

While this may provide a very elegant explanation to the observed relation, this analysis relies on the underlying assumption that the comoving luminosity and comoving temperature are related via $L' \propto (T')^2$, while one expect the comoving temperature to decay with radius.[36] Thus, an underlying assumption here is that the photospheric radius is roughly similar in many different GRBs, which is unknown. I further discuss this issue in section 7 below.

6. Broadening of the photospheric emission

Numerical simulations of jets propagating inside and outside the collapsing star[21,37–39] clearly demonstrate that part of the jet kinetic energy is dissipated at various radii, in many cases below the photosphere. Such a dissipation can result from recollimation shock with the collapsing stellar material, magnetic energy dissipation or internal collisions. The resulting spectra was studied by various authors, e.g., Refs.[19,25,40–42] to name a few.

In this scenario, the dissipated energy is used to heat the plasma, which is then characterized by 2 temperatures: an electron temperature T_e which is greater than the photon temperature. Under these conditions, the resulting spectrum above the thermal peak is mainly due to inverse Compton (IC) scattering of the photons inside the plasma. It depends mainly on 2 parameters: the number of scattering (namely, the optical depth at the location of the energy dissipation) and the available energy, namely the ratio between the electron and the photon field energies, u_{el}/u_{ph}.

Below the thermal peak, one may expect an additional modification due to synchrtron emission from the (newly) heated electrons. Above the thermal peak, multiple scattering broadens the peak; if the optical depth is high enough, a new thermal peak would emerge, at higher temperatures. But in the intermediate case, $\tau \lesssim 100$, there is no simple analytical solution, and one has to refer to numerical works,[25,30,43–45] which show the plethora of possible spectra.

Another, independent broadening mechanism to be considered is geometrical broadening, which is the relativistic version of the "limb darkening" effect. Even for a spherical explosion, the photospheric radius is a function of the angle to the line of sight, θ, via $r_{ph}(\theta) \propto \left(\Gamma^{-2} + \theta^2/3\right)$, where Γ is the Lorentz factor of the flow.[29] This implies that photons emerging from angles $\theta > \Gamma^{-1}$ escape the expanding plasma at large radii. Furthermore, the photons have a finite probability of escaping the expanding plasma at different radii, leading to the concept of "vague photosphere".[29,30] This distribution inherently results in broadening of the emerging signal.

The explosion, though is not expected to be spherical, but rather a jet-like, with a finite jet opening angle. The flow properties may best be approximated as $\Gamma(\theta) \propto \Gamma_0/\sqrt{(1+(\theta/\theta_j)^{2p}}$ (see simluation by[38]), where θ_j is the jet opening angle, and p represents the "steepness" of the velocity profile. In this case, the observed signal depends, in addition, on the viewing angle, θ_v.[46] This scenario naturally leads to an enhancement of the limb darkening effect, as the Doppler boost of photons emitted from larger angles and larger radii is considerably smaller than that of photons emitted from the central jet regions. As a result, these photons are observed at much lower energies, and the observed spectrum – purely from the photosphere – is nearly flat for a wide energy range, for different jet parameters and viewing angles.[46]

This scenario naturally results in a polarized signal, for an off-axis observer. The scattered photons are 100% polarized, the photon field is anisotropic near the photosphere, and the rotational symmetry is broken for $\theta_v > 0$ (observer off the jet axis). The resulting polarization can reach 10's of % ($Q/I \lesssim 40\%$ for an off-axis observer, with flux that is still detectable). Another prediction of the theory is $\pi/2$ shift in polarization angle,[47] with spectra that is so smeared it looks very different from a pure "Planck". Indeed, such a polarization angle change was recently detected by the ASTROSAT mission,[48] though its exact origin is still debated.

7. Back scattering photospheric model

An underlying assumption of the discussion above is that the source of photons is the expanding plasma inside the jet: either via acceleration of particles that radiate synchrotron, or that the photons are coupled to the plasma below the photosphere. However, one may envision a different scenario, in which, following an initial expansion of the jet which clears a cavity inside the collapsing star,[39,49] continuous production of pairs via, e.g., neutrino annihilation occurs close to the newly formed black hole. These pairs then annihilate to produce photons. The photons, in turn, propagate inside the empty funnel until being scattered by the expanding stellar "cork" (made of stellar material cleared by the jet and by the surrounding cocoon).

In this scenario, therefore, the photons are back scattered by the relativistically expanding cork ahead of them from behind. Due to the relativistic motion of the cork, in the frame of an observer at infinity these photons are scattered in the forward direction, at some angle to the cork propagation direction. Due to the different Doppler boosts, photons scattered at different angles are seen at different energies. The obtained spectra integrated over different viewing angles, $dN/d\epsilon \propto \epsilon^1$ for energies below the peak, resembles the observed one.[50] For hot cork, multiple scattering inside the cork leads to photon energy gain,and the high energy spectral slope obtained is also similar to the observed.[51]

Perhaps the greatest achievement of this model is its ability to naturally explain the $E_{pk} - E_{iso}$ correlation ("Amati" relation) as a natural outcome of observers located at different angles, without the need to invoke any additional underlying assumptions, as in the "classical" photospheric model discussed above.

8. Summary

Understanding the origin of GRB prompt emission remains one of the big puzzles in the study of gamma-ray bursts. It is of particular importance, due to the fact that understanding it directly enables to probe the key physical ingredients involved in producing the GRB phenomena.

In recent years, there is a healthy debate between different ideas of interpreting the observed signal. As it turned out, different models both seem to produce key parts of the spectra. However, the physical parameters required for the synchrotron radiation to be the dominant mechanism seem at odds with afterglow observations.

Photospheric emission model turned out to be much more complicated than initially thought. Various effects and mechanisms act to modify the observed signal, which does not resemble the textbook "Planck" function. Among them are the finite detector's bandwidth, the jet velocity profile and sub-photospheric energy dissipation. For jet viewed off-axis, as in the vast majority of jets, the observed signal may be highly polarized. Another major advantage is the ability to explain the observed $E_{pk} - E_{iso}$ correlation, which is a natural outcome of a model in which the source of photons is not relativistically moving, but rather the photons are back-scattered from the expanding cork.

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